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Abstract: Parallel pipelines are frequently installed over long distances, due to the difficulty in creating or maintaining the required corridor. This implies that a release in one pipeline can seriously affect another one. The main risks associated with this domino effect are the erosive action of fluid-sand jets and the thermal action of jet fires. In this paper a survey has been performed on the accidents that have occurred, and the diverse possibilities and the associated domino sequences are analysed. The probability of occurrence of this domino effect is a function of the location of the hole, the direction of the jet, the solid angle that the jet is outlining, the diameter of both pipelines, and the distance between them. A mathematical model has been developed to estimate this probability. The model shows how the probability of domino effect decreases with the distance and diameter of the source pipe, and increases with the diameter of the target pipe. The frequency of the domino effect can be estimated from this probability and from the frequency of the initiating pipe failure plus, in the case of jet fire impingement, the probability of ignition. The frequency of the secondary pipe failure thus calculated, always higher than the individual frequency of this pipe, allows obtaining more realistic risk analysis results.

HIGHLIGHTS

- In parallel pipelines domino effect can have a significant influence.
- Domino effect will be originated by jet erosion or jet fire impingement.
- The domino effect probability depends on the geometric arrangement of the system.
- A mathematical model has been developed to estimate domino effect probability.
- This probability allows a more realistic estimation of failure frequencies.

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ANALYSIS OF DOMINO EFFECT IN PIPELINES

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ABSTRACT

Parallel pipelines are frequently installed over long distances, due to the difficulty in creating or maintaining the required corridor. This implies that a release in one pipeline can seriously affect another one. The main risks associated with this domino effect are erosion by fluid-sand jets and the thermal action of jet fires. In this paper a survey has been performed on the accidents that have occurred, and the diverse associated domino sequences are analyzed. The probability of occurrence of domino effect is a function of the location of the hole, the jet direction and solid angle, the diameter of both pipelines and the distance between them. A mathematical model has been developed to estimate this probability. The model shows how the probability of domino effect decreases with the distance and diameter of the source pipe, and increases with the diameter of the target pipe. Its frequency can be estimated from this probability and from the frequency of the initiating pipe failure plus, in the case of jet fire impingement, the probability of ignition. The frequency of the target pipe failure thus calculated, always higher than its individual frequency, allows a more realistic risk analysis.

Keywords: Jet impingement, Jet fire, Pipe erosion, Impingement modeling.

1. Introduction

Pipelines are the most important and safe way to transport huge amounts of oil and other fluids to large distances, and to distribute them to the points where they are used. It is a relatively safe system; however, loss of containment events occur from time to time, due to bulldozers, corrosion, aging, landslides, etc. In such cases, a huge amount of flammable material can be released and this can lead to major accidents (i.e. explosions, fires environmental pollution).

While most accidents have occurred because of the aforementioned causes, in some of them the severity of the event has been increased due to the so-called domino effect [1]. Domino effect can enlarge the scale of an accident and the severity of its consequences. This can be especially important in industrial plants, due to the closeness of the diverse equipment units [2].

In the case of pipelines the situation is essentially different, as usually there are neither vessels nor other units in the near field. However, pipelines lay out over many

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kilometers crossing the country through forests, rivers and urban zones and, therefore, a hallway must be designed to allow this path. Such a hallway is often difficult to establish and it can be very expensive, and in many cases it is used for more than one pipe. Thus, parallel pipes, sometimes with a short separation between them, transporting gas, oil or water over long distances can be often found. The same situation exists in urban zones, where kilometers of pipes conveying gas, petrol or water are buried, together with other services such as electric wiring. Underground hallways in densely inhabited urban zones have sometimes a dense arrangement of parallel and crossing pipes and utilities, and this implies a certain risk associated to the potential interaction of these systems [3, 4].

In these situations, it is possible that a loss of containment occurred in a pipe affects another close pipe. This has happened in diverse accidents, with severe consequences on people or with environmental impact.

Several authors have assessed the impact of high pressure releases in parallel-running pipelines. Mohsin et al. [5] studied the underground natural gas pipeline safety distances, analyzing the possible outcomes of an accident associated with high-pressure water issuing from a pipe. Mazzola [6] assessed the consequences of high pressure releases of flammable gas from different rupture sizes in two parallel natural gas pipelines. Other authors [7–16] have focused on the metallurgical failure analysis of specific accidents in pipelines, caused by the action of a high-pressure jet issuing from a source pipe and damaging a second one. Wang et al. [17] analyzed the possible domino effect, in the event of the release from a pipeline, associated to thermal radiation, blast and ejected fragments.

However, none of these authors has attempted to develop a model allowing the assessment of how this domino effect can affect the frequency of failure of a given pipelines system. Such a tool would be quite useful for the risk analysis of pipeline transportation systems.

In this paper, a novel approach for the assessment of domino effect in pipelines is developed. Based on a historical survey of pipeline accidents, a mathematical model is proposed to estimate the probability of domino effect in parallel pipelines, aerial or buried, associated to a jet and to the resulting erosion or thermal effects. The model has been applied to two different accidental scenarios.

2. A survey of domino effect accidents in pipelines

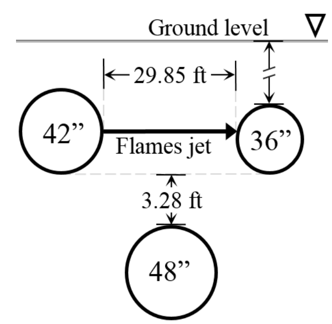
After a literature search, eight cases have been found of accidents involving parallel pipes accidents occurred in smaller urban pipes have not been included, nor accidents generated by other services (e.g. electrical lines). The available information has been summarized in Table 1.

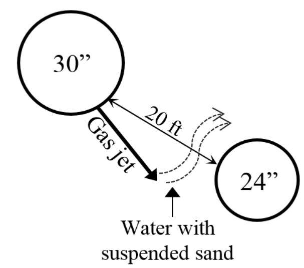
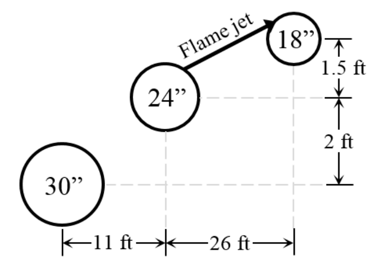
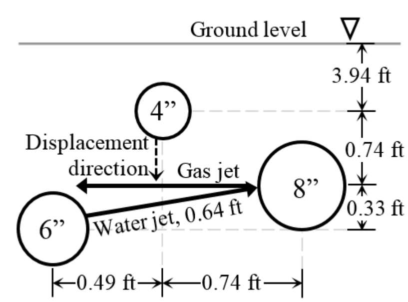
Natural gas was involved in seven accidents. The source pipeline conveyed water (four cases), natural gas (three cases) or oil (one case). In three cases three pipes were involved. The initial loss of containment in the source pipe was caused by corrosion or sabotage (two cases). Once the first jet of fluid appeared, the time to failure of the target pipe was known in one of the cases (80 min). The distances between both pipes ranged between 6 and 0.05 m.

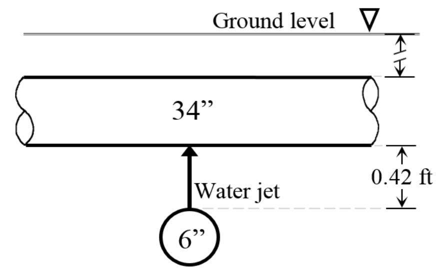
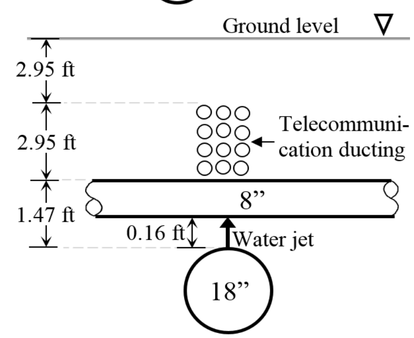
In three cases the failure of the target pipeline was due to a jet fire from oil (one case) or natural gas (two cases) release. In one of the natural gas jet fire cases, the distance between both pipes was 7.9 m and the time to failure was 20 min.

The features of these cases are essentially different from those found in the domino effect sequences occurred in process/storage plants, even though there can be some coincidence. In the case of plants, a significant number of equipment (vessels, columns, piping…) are located on a relatively reduced area, with rather short separation distances. This means that thermal radiation, overpressure or ejected fragments have a high probability of reaching a vulnerable element, often a vessel. Among the significant differences with respect to the domino accidents in pipelines, the following can be emphasized [1, 2]: the main initial causes in plants are mechanical failure and human factor, while the contribution of corrosion (quite important in pipelines) is very low; furthermore, only 10% of the initiating events occurred in on-plant pipes and associated valves. However, an aspect is relatively similar in both systems: the influence of "external events", which in plants constitutes 30% of initiating events, while in pipelines "third party activities" (often excavating machinery) reaches approximately 38%.

Table 1
Domino effect accidents in pipelines.

ID	Date, place	Source pipeline	Target pipeline 1	Target pipeline 2	Description	Diagram of the layout of the pipelines	Reference
		Diameter/Material transported/Grade/Type of coating/Operating pressure					
1	1984, Venezuela	8 in/Oil/–/–/5171 kPa	16 in/Natural gas/–/–/–	–	An 8-in oil pipe fractured. Ignition occurred and the fire led to rupture of the 16-in gas pipe, creating a hole (1.5-in), which resulted in a jet fire, leading to further pipe ruptures. Economic losses rose to US$ 81,900,000.	–	[18]
2	1990, USA	6 in/Water/Cast-iron /–/–	4 in/Natural gas /Cast-iron/–/2.25 kPa	–	Water leaking from a circumferential crack in a 6-in main eroded the soil foundation beneath a 4-in cast-iron gas pipeline, which later cracked due to soil loads from above, releasing natural gas that eventually exploded and burned. Two houses were destroyed. One person was killed and nine others were injured.	–	[19]
3	1995, Canada	42 in/Natural gas /CSA-Z245.2 X65 /asphalt enamel, asbestos, Kraft paper/6068 kPa	36 in/Natural gas /API X60/ mastic primer, asphalt enamel, asbestos, Kraft paper/6068 kPa	48 in/Natural gas /–/–/–	Stress corrosion cracking caused a rupture (34.5 ft. in longitudinal direction) in the 42-in gas pipeline. The gas released caught fire and the heat affected the 36-in gas pipeline, causing its rupture (27.9 ft. in longitudinal direction). A third 48-in gas pipeline was exposed to the fire but did not rupture. 19,600,000 m^3 of natural gas were consumed. Crater area: 725 m^2.		[20]

ID	Date, place	Source pipeline	Target pipeline 1	Target pipeline 2	Description	Diagram of the layout of the pipelines	Reference
		Diameter/Material transported/Grade/ Type of coating/Operating pressure					
4	2003, Pakistan	30 in/ Natural gas/ Carbon steel/–/ 7943 kPa	24 in/ Natural gas/ Carbon steel/–/ 7943 kPa	–	An explosion (sabotage) caused the rupture of the 30-in aerial gas pipe located over an irrigation canal, creating a hole (4 in x 10 in). The gas jet caused a sandblasting action on the 24-in buried gas pipe. After 80 minutes, the 24-in pipe broke.		[7]
5	2004, Pakistan	24 in/ Natural gas/ Carbon steel/ Bitumen/ 9928 kPa	18 in/ Natural gas/ Carbon steel/ Bitumen/ 9928 kPa	30 in/ Natural gas/ Carbon steel Polyethylen e/9928 kPa	An explosion (sabotage) caused the rupture of the 24-in aerial gas line. The gas released caught fire; the jet fire affected the 18-in aerial gas pipe. After 20 minutes, the 18-in pipe failed. The thermal radiation also affected the coating of the 30-in pipe.		[8]
6	2009, Malaysia	6 in/ Water/ Asbestos/– /1000 kPa	8 in/ Natural gas/ Carbon steel (API 5L X42)/– /1800 kPa	4 in/ Natural gas/ Polyethylen e/–/ 345 kPa	A crack in the 6-in asbestos pipe originated a water jet; this sandblasting action affected the 8-in gas pipe, creating a hole (0.39 in), which resulted in a natural gas jet. Both jets caused the displacement of the supporting soil underneath the 4-in gas pipe causing it to move downwards, until it located in the direction of impact of the gas jet.		[9–13]

ID	Date, place	Source pipeline	Target pipeline 1	Target pipeline 2	Description	Diagram of the layout of the pipelines	Reference
		Diameter/Material transported/Grade/ Type of coating/Operating pressure					
7	2010, USA	6 in/ Water/–/–/–	34 in/Oil/ API X52/ Polyken polyethylene tape/4268 kPa	–	Corrosion in a buried water pipe produced three holes, one of which measured 5.1-in. The water-jet caused a sandblasting action on the 34-in oil pipe, creating a hole (1.5 in). 6,430 barrels were spilled, causing economic losses of US$ 46,617,000.		[21]
8	2012, Malaysia	18 in/ Water/ Steel 430/ Bitumen enamel with fiberglass/ 900 kPa	8 in/ Natural gas/API 5L X42/ Coal-tar enamel with fiberglass/ 1700 kPa	–	Failure in the weld joint of the 18-in water pipe produced high-pressure water jet that affected the 8-in gas pipe. The sandblasting action created three separate pinholes with difference sizes.		[14–16]

3. Domino effect possibilities

Once a first release occurs, the possible domino effect can follow diverse sequences. If there is a hole in a pressurized pipe, the fluid will be released at a very high velocity. In the case of a gas, if $P_{pipe}/P_{outside}$ > 1.9 the gas will exit at the sound velocity; for liquids or two-phase flow the velocity will be lower. This may have serious effects on other neighboring pipes, associated to erosion and thermal impact. However, the situation will depend on whether the pipelines are aerial or buried. Another important aspect is whether the fluid is or not flammable; if it is flammable, ignition is possible for aerial pipelines, and also for buried ones if the generation of a crater by the source jet allows it. And, finally, with buried pipes, the erosion will depend on the probable existence of an abrasive solid (sand or gravel). Majid et al. [22] performed tests to investigate the erosive wear of natural gas pipelines (API 5L X42 steel pipe) subjected to the action of a water-sand jet issuing from a 5 mm diameter orifice; they found a maximum wall thinning rate of 1.1×10^{-5} m hr^{-1}.

Another important aspect is the duration of the release. In aerial pipes, the loss of containment will probably be detected, while if they are buried, the detection will be more difficult. If the release is important, the decrease in flow rate or in pressure may indicate it. However, if it is relatively small, detection can be challenging and therefore the escape could be much longer (small release flow rates in water pipes are often disregarded). The diverse possible sequences have been summarized (Fig. 1). The final accidental scenarios of these sequences –pipe failure due to thermal impact, erosion or thermal/blast impact– have been established, based on the historical survey and risk analysis expertise.

The initiating event is a release through a hole in the source pipe. There are two possibilities: aerial or buried pipes. In aerial pipes, if the released fluid is flammable and is ignited, there is a certain flames impingement probability on the target pipe. If this pipe conveys gas and it is not adequately fireproofed, the probability of failure in a rather short time is very high. Hemmatian et al. [23] have drawn attention to the high heat fluxes in the case of jet fire impingement (see the values given in Section 5), and to the short time to failure (as short as a few minutes in some cases) that can occur when the heated wall is not wetted by a liquid. However, if the target pipe conveys a high flow at high pressure, the heat transfer coefficient to internal fluid could be sufficient to prevent failure.

If the target pipe conveys two-phase flow, the possibility of pipe failure due to the high temperature reached by the pipe wall should also be considered. Instead, if the pipe conveys a liquid, this will cool the pipe wall avoiding pipe failure. However, the flow in the target pipe can be shut off if blocking valves are shutdown; this again could lead to pipe failure. Furthermore, if the jet fire flame shape is modified by a rather congested arrangement and flames engulf the target pipe –without any jet fire direct impingement-, then this pipe could stand [6]. If there is no flames impingement, the target pipe will probably not be affected. However, if it receives a strong thermal radiation –and it conveys a gas– it could still fail.

If the released fluid is flammable and there is no immediate ignition, a flash-fire or an explosion is still possible (late ignition); in this case, both pipes could be damaged (blast) or the target pipe could be affected by the jet fire following the fire flashing back.

If both pipes are buried, the situation is somewhat different. If the release is flammable there is still the possibility of ignition, but only if the released jet or an explosion creates a crater. If this happens, the diverse sequences are similar to those commented previously. If there is no ignition but the jet impinges on the target pipe, it will entrain solid particles and the resulting fluid/solid jet will be highly abrasive. If the hole in the source pipe is small and the released flow rate is not detected, the probability that it will finally cause another release in the target pipe is rather high; even if there is no direct jet impingement, the fluid/solid blasting action could erode it [7], decreasing its thickness in such a way that it could be unable to stand the inside pressure and it would fail. Finally, if there is no immediate ignition but the released fluid is flammable, a flash-fire and/or an explosion can occur. This will happen if the released gas flows through the soil and enters into the atmosphere, or if a liquid after saturating the soil flows above ground and evaporates. If this happens and, furthermore, a crater has been formed, the fire will travel back to the fluid outlet and a jet fire will occur, with the consequent potential damage to the target pipe.

4. Modeling jet impingement on the target pipe

A jet issuing from a hole in a source pipe can affect a target pipe nearby depending on its direction and on the geometric configuration of the system: pipes diameters, distance between pipes and location of the hole in the source pipe. Let us consider a simple configuration of two pipes of equal dimensions. A jet can take many different directions (Fig. 2a) within a range of π radians (which corresponds to the plane tangent to the pipe wall at the hole location). At the same time, any hole located at the source pipe within the half of the perimeter adjacent to the secondary pipe, can impinge on the target (Fig. 2b). The angle of the fluid jet α_n will change with fluid properties and environment circumstances [5, 24].

Thus, the probability of jet impingement depends on *i)* the section of the perimeter of the source pipe where the presence of a hole may generate a jet impingement scenario and *ii)* the angle and direction of this jet.

Let us consider the general case where two pipes (source pipe of radius *r* and target pipe of radius *R*) are located *d* meters apart (Fig. 3). We define Δ as the angle delimiting the section of the perimeter of the source pipe that can contain a hole issuing a jet that may impinge the target pipe. Any jet issuing from the arch delimited by the angular section 2π-Δ will not impinge on the target. Δ can be expressed as a function of *R*, *r* and *d* by applying trigonometry relations to the shaded triangle of Fig. 3, as Δ is the conjugated angle of Θ (Δ and Θ are delimited by the external tangents to the two circumferences that represent both the source and the target pipe):

$$\Delta = 2\left(\pi - arccos\left(\frac{R-r}{d}\right)\right) \qquad (1)$$

Now, let us consider a one-dimensional jet issuing from a hole located at an angle δ within the Δ circular section (Fig. 4). The overall angle of impingement (i.e. the range of directions that the one-dimensional jet could take implying impingement) can be represented by 2β.

The value of angle β can be deduced by analyzing the two contiguous triangles represented in Fig. 4:

$$\beta = \arcsin \frac{R}{\sqrt{d^2 + r^2 - 2rd \cdot cos\delta}} \tag{2}$$

Note that β may have some physical/geometrical restrictions in some regions of the arch delimited by Δ. These restrictions are related to the internal tangent between both pipes (Fig. 5). Let us name δ_t the angle that references the position of the tangential point of the source pipe with one of the internal tangents between the circumferences representing both pipes. δ_t in turn, splits the section of the source pipe perimeter delimited by $\Delta/2$ into two arches: L_1 and L_2. If a hole is formed within the arch L_2 (Fig. 4), 2β will not have any geometrical limit, since the tangent plane at the jet's orifice will fall always below the internal tangent between pipes. If a hole is formed in the point of intersection between L_1 and L_2, 2β will still be unrestricted, since 2β will seat on/be delimited by the internal tangent. However, if a hole is formed within L_1, the overall angle that a jet may cover will be always lower than 2β, because the tangent plane will be located above the internal tangent. This is the case illustrated at the bottom image of Fig. 5, where the angle λ represents the narrow range that the jet direction may take issuing from a hole in L_1.

4.1. Probability model

To assess the probability of domino effect in pipelines, several aspects must be considered: the hole location, the jet direction and the solid angle that the jet is outlining. For the sake of simplicity, we propose a probability model for a one-dimensional jet impingement (i.e. the solid angle of the jet will not be taken into account). Given two pipes (source pipe of radius r and target pipe of radius R, being $r < R$) with their centers separated d meters apart, the probability (P) that a jet issuing from the source pipe impinges on the target pipe is expressed by:

$$P = P_1 \cdot P_2 \tag{3}$$

where P_1 is the probability that a hole formed in the source pipe may imply a risk of impingement, and P_2 is the probability that a jet issuing from a hole with risk of impingement may actually have the appropriate direction to reach the target pipe. P_1 is expressed as:

$$P_1 = \frac{\Delta}{2\pi} \tag{4}$$

P_2 will depend on the exact location of the hole within the arch delimited by Δ, whether it is within the L_1 or L_2 section. Let us define P_{2-L_2} as the impingement probability of a jet issuing from a hole in L_2, and P_{2-L_1} as the impingement probability of a jet issuing from a hole in L_1.

Following Eq. (2), P_{2-L_2} can be written as:

$$P_{2-L_2} = \frac{2\beta}{\pi} = \frac{2\ \mathrm{arcsin}\dfrac{R}{\sqrt{d^2 + r^2 - 2rd \cdot cos\delta_{L_2}}}}{\pi} \tag{5}$$

where δ_{L_2} is the angle delimiting the position of an orifice within L_2 (Fig. 6). To simplify, we consider the orifice to be located at the medium of the segment L_2. Then:

$$\frac{\delta_{L_2}}{2\pi} = \frac{L_2/2}{2\pi r} \tag{6}$$

and hence,

$$\delta_{L_2} = \frac{L_2}{2r} \tag{7}$$

In turn, from Fig. 6, the following trigonometric relationships can be deduced:

$$\delta_t = arccos\left(\frac{R + r}{d}\right) \tag{8}$$

$$\delta_t = \frac{L_2}{r} \tag{9}$$

By combining the last two equations, the analytical solution for L_2 and hence P_{2-L_2} is completely defined:

$$L_2 = r \cdot arccos\left(\frac{R + r}{d}\right) \tag{10}$$

Concerning P_{2-L_1}, it will be lower than P_{2-L_2} due to the physical limits of β previously mentioned. Thus, it is reasonable to model this probability by:

$$P_{2-L_1} = q \cdot\ P_{2-L_2} \tag{11}$$

where q is a reduction factor ranging between 0 and 1. We have made an educated guess of q, based on the real configurations found in the literature review and on other arrangements (see Table 1, ID 3, 4, 5, and 6). We have found the angular values for the ranges of possible directions that a one-dimensional jet would take issuing from an orifice located at $L_2/2$ (i.e. values of 2β of real configurations), as well as the same magnitude for a jet issuing from an orifice located at $L_1/2$ (i.e. values of λ for real configurations). The ratio between both values has given an estimation of q (mean value of 0.45).

From P_{2-L_1} and P_{2-L_2}, P_2 can be expressed as the weighted combination of both:

$$P_2 = s \cdot P_{2-L_1} + (1 - s) \cdot P_{2-L_2} \tag{12}$$

with:

$$s = \frac{L_1}{L_1 + L_2} \tag{13}$$

Finally, L_1 can be:

$$L_1 = r \cdot \left(\frac{\Delta}{2} - \delta_t\right) \tag{14}$$

4.2. Model performance

The prediction from the model can be observed in Fig. 7. We have plotted the probability of jet impingement for diverse scenarios of source and target pipe of the same diameter (6, 12, 24, 36 and 48 inches), as a function of different effective pipe distances:

$$d' = d - 2r \tag{15}$$

This model shows clearly how, as the distance between both pipes decreases, the probability of a domino effect on the target pipe increases. For example, for two pipes with D = 12 in, the probability of impingement is 0.135 for a distance d' = 0.1 m, and decreases to 0.038 if the distance between pipes increases up to 1 m. The worst case analyzed (d' = 0.01 m) gives domino effect probabilities in the range 0.19-0.22. The probability is higher for the pipes with a larger diameter, due to the larger size of the target. For large separation distances (i.e. 10 m) –therefore with no possible domino effect– the theoretical probability is less than 3 x 10^{-3} for the 6 inches pipes scenario and less than 2 x 10^{-2} for the 48 inches pipes scenarios. Moreover, the probability is the same (P = 0.116) for all cases when the separation d' is D (data not shown).

The model has been developed for the general case of source pipes smaller (or equal) in diameter than target pipes. However, due to the symmetry of the geometrical system, the model can be easily rewritten for the cases where the source pipe is bigger than the target (Fig. 8). The summary of the modified equations to be used –together with original expressions (1), (3), (11), (12) and (13)– in these latter cases are as follows:

$$P_1 = 1 - \frac{\Delta}{2\pi} \tag{16}$$

$$P_{2-L_2} = \frac{2\arcsin \dfrac{r}{\sqrt{d^2 + R^2 - 2Rd \cdot cos\delta_{L_2}}}}{\pi} \tag{17}$$

$$\delta_{L_2} = \frac{L_2}{2R} \tag{18}$$

$$L_2 = R \cdot arccos\left(\frac{R+r}{d}\right) \tag{19}$$

$$L_1 = R \cdot \left(\pi - \frac{\Delta}{2} - \delta_t\right) \tag{20}$$

In Fig. 9 we have plotted the variation of the probability of domino effect as a function of distance for four scenarios found in the literature review. Three of them (ID 3, 4, 5 and 6) have source pipe diameters larger than the target, whereas the other one (ID 6) has the source pipe smaller than the target pipe. The latter scenario had a higher probability of domino effect (0.087) than the others, due to the shorter distance between pipes. Reported accidents occurred in Canada (1995) and Pakistan (2003 and 2004) had all probabilities lower than 1.5 x 10^{-2}, all them with distances bigger than 6 m.

The model developed allows us to explore differences between systems (Fig. 10 and Fig. 11). For a certain source pipe, the model shows how the probability of domino effect increases with the target pipe diameter, since the more target pipe surface exposed the more probable for a jet issuing from the source pipe to impinge. It can also explain the differences originated as a function of source pipe diameters. For instance, data in Figs. 10 and 11 show how for small target pipes (i.e. 6-12 inches) and short distances (less than 0.25 m) the probability of jet impingement is between 2 and 2.7 times bigger with a source pipe of 6 inch than with a source pipe of 48-in. For other cases (target pipes of 24-48 inch and distances from 0.5 to 1 m), the probability will still be bigger (1.3-2 times) for smaller source pipes, but less in absolute values.

5. Jet fire

If the released jet is flammable and the pipe is aerial or a crater has been formed, there is possibility of ignition. Ignition sources are often related to human activity, road traffic, etc.; therefore, the ignition probability will vary significantly with the environmental circumstances. If the jet is ignited, then a jet fire will occur.

Jet fires are associated to very high heat fluxes as they entrain a large amount of air and the combustion is much better than in other accidental fires. The thermal effect on a given equipment or a pipe will be the one due to the thermal radiation if there is no direct contact with flames, or that associated to both radiation and convection if there is flames impingement.

Although the thermal radiation decreases quickly with the distance, in some cases its effects on the pipe wall can be dangerous and can lead to failure. The worst case happens when there is flame impingement, as the thermal flux is very high; the following approximate values can be assumed [23, 25–27]:

- Natural gas: 200 kW m^{-2},
- Propane gas: 300 kW m^{-2},
- Propane, two-phase: 180 kW m^{-2}.

Again, the possibility of impingement depends on the relative position of the source pipe hole and the target pipe. However, another element appears now: the lift-off distance. The lift-off is the centerline distance from the gas release point to the start of the detached and stabilized flame; its magnitude can be determinant from the point of view of thermal domino effect. If a pipe is located at a distance from the source pipe that is shorter than the lift-off, the flames probably will not affect it. As for the maximum jet fire flames reach, it will be the length of the visible flame plus the lift-off.

Diverse models have been proposed to predict the shape and size of jet fires. These variables can be described approximately in a simple way for vertical jet fires, but the situation becomes more complex when the jet fire is horizontal or inclined. In this case, the jet is straight, following the outlet jet main axis, while the high momentum controls it; however, it moves up due to buoyancy as the linear velocity inside it decreases. For the sake of simplicity, here only a simple vertical jet model is commented; in fact, for short distances it can also be applied to other orientations of jet fire. The following expressions have been proposed for propane jet fires [28–30].

Lift-off distance:

$$S = \frac{6.4\pi \cdot d_{hole} \cdot u_j}{u_{av}} \tag{21}$$

Flame length:

$$L = 5.8 \cdot d_{hole} \cdot Re^{0.27} \tag{22}$$

The contour of jet fire flames is difficult to define. Accepting that it can be defined by the isotherm of 800 K –practically the Draper point– it can be assumed to be a cylinder with an “equivalent diameter” given by:

$$D_{eq} = \frac{L}{7} \tag{23}$$

This model implies a conservative approach, as it predicts larger lengths than those designed for inclined or horizontal jets. It was obtained for the range $5 \times 10^{-4} < Re < 5 \cdot 10^{-6}$. For higher *Re* values, more complex models should be applied [31].

Thus, for a given jet fire and source and target pipes system, there will be flames impingement if the jet fire is directed towards the target pipe and the distance between both pipes is in the range $S < d' \leq (S+L)$ (see Fig. 12).

With this simplified approach, the probability of target pipe failure can be estimated. If there is no flames impingement but only thermal radiation, the evaluation of the probability of serious damage on the target pipe is much more complex and is not treated here.

6. Frequency of the domino effect

The domino effect frequency can be estimated from the frequency of the initial release at the source pipe and the probability of damage to the target pipe.

Concerning the pipe failure frequencies, they will depend on several factors: pipe diameter, protection measures and location (in urban zones aggressions from third parties could be significant; in rural areas natural impacts such as landslides could be expected). Diverse institutions have proposed values taken from historical analyses; Table 2 shows average pipeline failure frequencies of PHMSA, TSB and CONCAWE databases (period 2004-2011).

Table 2
Pipeline failure frequencies (m^{-1} $year^{-1}$).

	PHMSA [32]	TSB [33]	CONCAWE [34]
Full bore rupture	3.05×10^{-5}	4.30×10^{-6}	8.35×10^{-6}
Hole: d > 10 mm (maximum ½ DN)	9.71×10^{-5}	1.37×10^{-5}	2.66×10^{-5}

If *A* refers to the source pipe and *B* to the target pipe, the failure frequency of the target pipe, $f(B)_{overall}$, can be calculated:

$$f(B)_{overall} = f(B/A) + f(B) \tag{24}$$

where *f(B/A)* is the failure frequency of target pipe due to a previous failure of the source pipe, and *f(B)* is the failure frequency of the target pipe, independently of the presence of the source pipe.

f(B/A) is calculated from the pipeline failure frequencies of Table 2 and the probabilities previously explained, and *f(B)* is taken also from the values of Table 2, considering that initially each pipe has its own failure frequency, independently of the fact of being located together. Therefore:

$$f(B)_{overall} = f(A) \cdot P_{domino\ A \to B} + f(B) \tag{25}$$

In the event of a jet fire, the ignition probability should also be introduced:

$$f(B)_{overall} = f(A) \cdot P_{domino\ A \to B} \cdot P_{ignition} + f(B) \tag{26}$$

The ignition probability will depend on the existence of ignition sources and will change along the whole pipeline length, although sometimes an average value could be used. It will depend also on the conveyed fluid; for example, an average value of 2×10^{-2} has been proposed by EGIG [35] for natural gas, although for urban zones a minimum value of 0.7 is assumed and 0.8 is often applied.

The following examples illustrate these calculations.

General scenario: Two pipes, a 6-inch diameter pipe (source) and a 36-inch diameter pipe (target), d_{hole} = 20 mm in the source pipe. The release frequency in the source pipe is 9.71×10^{-5} m^{-1} $year^{-1}$ (PHMSA).

Case 1: Erosion by a jet. The two pipes are buried and separated by d' = 0.25 m. The source pipe conveys water and the target pipe natural gas.

Case 2: Gas jet fire impingement. The two pipes are aerial and separated by $d' = 0.5$ m. The source pipe conveys propane (20 ºC, 6 bar) and the target pipe natural gas. An ignition probability of 0.8 has been assumed.

Eqs. (1-13) and (25-26) have been applied to calculate the impingement probability on the target pipe and the final failure frequency of this pipe. The values obtained for both cases are shown in Table 3.

Table 3
Impingement probability and failure frequency of target pipe.

Variable	Case 1	Case 2
Δ	4.157 rad	3.897 rad
β	0.695 rad	0.492 rad
P_{2-L_2}	0.442	0.313
P_{2-L_1}	0.199	0.141
q	0.45	0.45
P_1	0.662	0.620
P_2	0.295	0.232
P	0.195	0.144
Lift-off	n.a.	[a]
Re	-	3,827,200
S	-	0.25 m
L	-	6.9 m
$S + L$	-	7.15 m [b]
D_{eq}	-	0.98 m
$f(B)_{overall}$	$9.71 \cdot 10^{-5} \cdot 0.195 + 9.71 \cdot 10^{5} = 1.16 \cdot 10^{-4}$ m^{-1}year^{-1}	$9.71 \cdot 10^{-5} \cdot 0.144 \cdot 0.8 + 9.71 \cdot 10^{5} = 1.08 \cdot 10^{-4}$ m^{-1}year^{-1}

[a] Assuming a choked flow (P_{choked} = 3.4 bar, T_{choked} = 272 K) with an outlet velocity of 243 m s^{-1} (speed of sound).
[b] The separation distance between both pipes is included in the range of S < d' ≤ (S+L), so if the jet fire is directed towards the target pipe there will be flames impingement.
n.a. Non applicable

7. Conclusions

The analysis of diverse accidents occurred confirm that when parallel pipelines are installed in the same hallway, the possibility of a loss of containment in one of them affecting the others should not be neglected. The so called domino effect has been observed to be associated to two potential damages: erosion by a fluid-soil abrasive jet in buried pipes, or thermal impact by a jet fire, mainly in aerial pipes, in the case of flammable substances. This has an influence on the failure frequency of the system, which should not be neglected in a risk assessment.

The analysis performed has shown that the overall failure frequency depends on the geometry of the system, i.e. pipes diameters and distance between pipes. A mathematical model has been developed to estimate the probability of domino effect in pipelines. It has been solved by applying an empirical component which has been established according to the configuration of the accidental scenarios found in the literature survey. It allows the analysis of the influence of the diverse variables on the domino effect probability. This probability has been observed to decrease as the distance between both pipes increases, and as the diameter of the target pipe decreases and the diameter of the source pipe increases. It has to be highlighted that for short separation distances and large diameters of the target pipe, the probability can reach significant values, between 0.2-0.3, which have relevant safety implications, since this probability straightly implies an increase of the overall pipeline failure frequency. Frequencies taking into consideration the probability of domino effect will provide more realistic and accurate risk analysis results, hence generally leading to safer outcomes.

Further work will be devoted to improve the model in order to surpass their initial simplifications (i.e. one dimensional jet hypothesis, empirical component) and to enlarge its applicability by considering other already existing pipelines configurations like crossing pipes in urban zones.

Notation

d	Distance between pipes centers, m
d'	Effective distance, m
D	Pipe diameter, m
D_{eq}	Jet fire equivalent diameter, m
d_{hole}	Hole diameter, m
DN	Nominal diameter, inch or m
$f(A)$	Source pipe failure frequency, m^{-1} year^{-1}
$f(B)$, $f(B)_{overall}$	Target pipe failure frequency, m^{-1} year^{-1}
$f(B/A)$	Failure frequency of target pipe due to domino effect, m^{-1} year^{-1}
L	Jet flames length, m
L_1	Source pipe section delimited by internal and external tangents between both pipes, m
L_2	Source pipe section delimited by the internal tangent between pipes and the line linking their centers, m
$P, P_{domino\ A\to B}$	Probability of domino effect, -
P_1	Probability that a hole in the source pipe may imply impingement, -
P_2	Probability that a jet from a hole with risk of impingement may reach the target pipe, -
P_{2-L_1}	Impingement probability of a jet from a hole located in L_1, -
P_{2-L_2}	Impingement probability of a jet from a hole located in L_2, -
$P_{impingement}$	Probability of jet impingement, -
$P_{iginition}$	Jet ignition probability, -
q	Reduction factor, -

r	Source pipe radius, m
R	Target pipe radius, m
Re	Reynolds number, -
s	Proportion factor -
S	Lift-off, m
u	Velocity at the gas outlet, $m \cdot s^{-1}$
u_{av}	Average jet velocity, $m \cdot s^{-1}$
u_j	Jet velocity at gas outlet, $m \cdot s^{-1}$
Δ	Angle formed by the external tangents of two pipes, delimiting a circular sector at the smallest pipe, rad
α_n	Jet angle jet, rad
β	Half solid angle of jet impingement, rad
δ	Angle delimiting the position of a hole, rad
δ_{L_2}	Angle delimiting the position of a hole within L_2, rad
δ_t	Angle giving the intersection between L_1 and L_2, rad
θ	Angle formed by the external tangents of two pipes, delimiting a circular sector at the largest pipe, rad
λ	Angle covering the narrow range that the jet direction may take issuing from a hole in L_1 section, rad
μ	Dynamic viscosity, kg m^{-1} s^{-1}
ρ	Density, kg m^{-3}

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References

[1] G. Reniers, V. Cozani, Features of escalation scenarios. In: G. Reniers, V. Cozzani (Eds.), Domino Effects in the Process Industries, Modelling, Prevention and Managing, vol. 3, Elsevier, Waltham, MA, USA, 2013, pp. 30–42, http://dx.doi.org/10.1016/B978-0-444-54323-3.00003-8.

[2] B. Hemmatian, B. Abdolhamizadeh, R.M. Darbra, J. Casal, The significance of domino effect in chemical accidents, J. Loss. Prevent. Proc. 29 (2014) 30–38.

[3] J. Casal, J. Cisteró, J.M. Tort, Some risks of energy distribution. Analysis of an explosion involving electrical and gas networks, Loss Prev. Saf. Prom. Proc. Ind. 1 (1995) 565–575.

[4] NTSB (National Transportation Safety Board) 2001, Natural gas explosion and fire, NTSB/PAR-01/01 (PB2001-916501), Washington.

[5] R. Mohsin, Z.A. Majid, M.Z. Yusof, Safety distance between underground natural gas and water pipeline facilities, Reliab. Eng. Syst. Safe. 131 (2014) 53–60.

[6] A. Mazzola, Thermal interaction analysis in pipeline systems: A case study, J. Loss. Prevent. Proc. 12 (1999) 495–505.

[7] F. Hassan, J. Iqbal, Consequential rupture of gas pipeline, Eng. Fail. Anal. 12 (2006) 127–135.

[8] F. Hassan, F. Ahmed, Metallurgical analysis of high pressure gas pipelines rupture, Pak. J. Engg. & Appl. Sci. 1 (2007) 14–23.

[9] Z.A. Majid, R. Mohsin, Z. Yaacob, Z. Hassan, Failure analysis of natural gas pipes, Eng. Fail. Anal. 17 (2010) 818–837.

[10] Z.A. Majid, R. Mohsin, M.Z. Yusof, Erosive wear of natural gas pipes due to high velocity jet impact: physical examination and experimental study, Jurnal Teknologi 56 (2011) 1–25.

[11] Z.A. Majid, R. Mohsin, M.Z. Yusof, Erosive wear of natural gas pipes due to high velocity jet impact: computer simulation study, Journal Teknologi 56 (2011) 27–52.

[12] Z.A. Majid, R. Mohsin, Failure investigation of natural gas pipeline, Arab. J. Sci. Eng. 37 (2012) 1083–1088.

[13] Z.A. Majid, R. Mohsin, M.Z. Yusof, Experimental and computational failure analysis of natural gas pipe, Eng. Fail. Anal. 19 (2012) 32–42.

[14] Z.A. Majid, R. Mohsin, Multiple failures of API 5L X42 natural gas pipeline, Eng. Fai. Anal. 31 (2013) 421–429.

[15] R. Mohsin, Z.A. Majid, M.Z. Yusof, Multiple failures of API 5L X42 natural gas pipe: Experimental and computational analysis, Eng. Fail. Anal. 34 (2013) 10–23.

[16] R. Mohsin, Z.A. Majid, F.L. Tan, Numerical analysis of wall shear patterns on the external wall of an API 5L X42 natural gas pipe, Eng. Fai. Anal. 48 (2015) 30–40.

[17] Z. Wang, Z. Fu, Y. Zou, L. Liu, H. Liu. Study on risk assessment of urban gas pipeline based on domino effect, International Conference on Pipelines and Trenchless Technology 2011 (2011) 1720–1727.

[18] MHIDAS (Major Hazardous Incident Data Service) 2007, in AEA technology. London: HSE-Health and Safety Executive (United Kingdom).

[19] NTSB (National Transportation Safety Board) 1990, Pipeline Accident Brief No. DCA-90-FP-001, Explosion and fire, Allentown, Pennsylvania, August 29, 1990. Washington.

[20] TSB (Transportation Safety Board of Canada) 1995, Commodity Pipeline Occurrence Report P95H0036, Natural gas pipeline ruptures, Rapid City, Manitoba, July 29, 1995. Canada.

[21] NTSB (National Transportation Safety Board) 2013, Large crude oil spill from damaged Enbridge energy pipeline, DCA-10-FP-009, Washington.

[22] Z.A. Majid, R. Mohsin, F. Omar, Erosive wear of natural gas pipeline, Jurnal Teknologi 49F (2008) 341–356.

[23] B. Hemmatian, E. Planas, J. Casal, Fire as a primary event of accident domino sequences: The case of BLEVE, Reliab. Eng. Syst. Safe. 139 (2015) 141–148.

[24] B. Cushman-Roisin, Environmental fluid mechanics, John Wiley and Sons, Inc., New York, 2014.

[25] I. Bradley, Severe jet fires and vapor explosions, Hydrocarbon Processing May (2012) T85–T88.

[26] B. Kozanoglu, L. Zárate, M. Gómez-Mares, J. Casal, Convective heat transfer around vertical jet fires: An experimental study, J. Hazard. Mater. 197 (2011) 104–108.

[27] B.J. Lowesmith, G. Hankinson, M.R. Acton, G. Chamberlain, An overview of the nature of hydrocarbon jet fire hazards in the oil and gas industry and a simplified approach to assessing the hazards, Process Saf. Environ. 85 (3) (2007) 207–220.

[28] A. Palacios, M. Muñoz, J. Casal, Jet fires: an experimental study of the main geometrical features of the flame in subsonic and sonic regimes, AIChE J. 55 (2009) 256–263.

[29] A. Palacios, J. Casal, Assessment of the shape of vertical jet fires, Fuel 55 (2011) 824–833.

[30] T.A. Brzustowski, Flaring in the energy industry, Prog. Energy Combust. Sci. 2 (3) (1976) 129–141.

[31] J. Casal, Evaluation of the effects and consequences of major accidents in industrial plants, Elsevier, Amsterdam, 2008.

[32] PHMSA (Pipeline and Hazardous Materials Safety Administration) 2014, All Reported Pipeline Incidents. http://primis.phmsa.dot.gov/comm/reports/safety/Allpsi.html?nocache=4168.

[33] TSB (Transportation Safety Board of Canada) 2014, Statistical Summary Pipeline Occurrences 2013. http://www.tsb.gc.ca/eng/stats/pipeline/2013/sspo-2013.pdf.

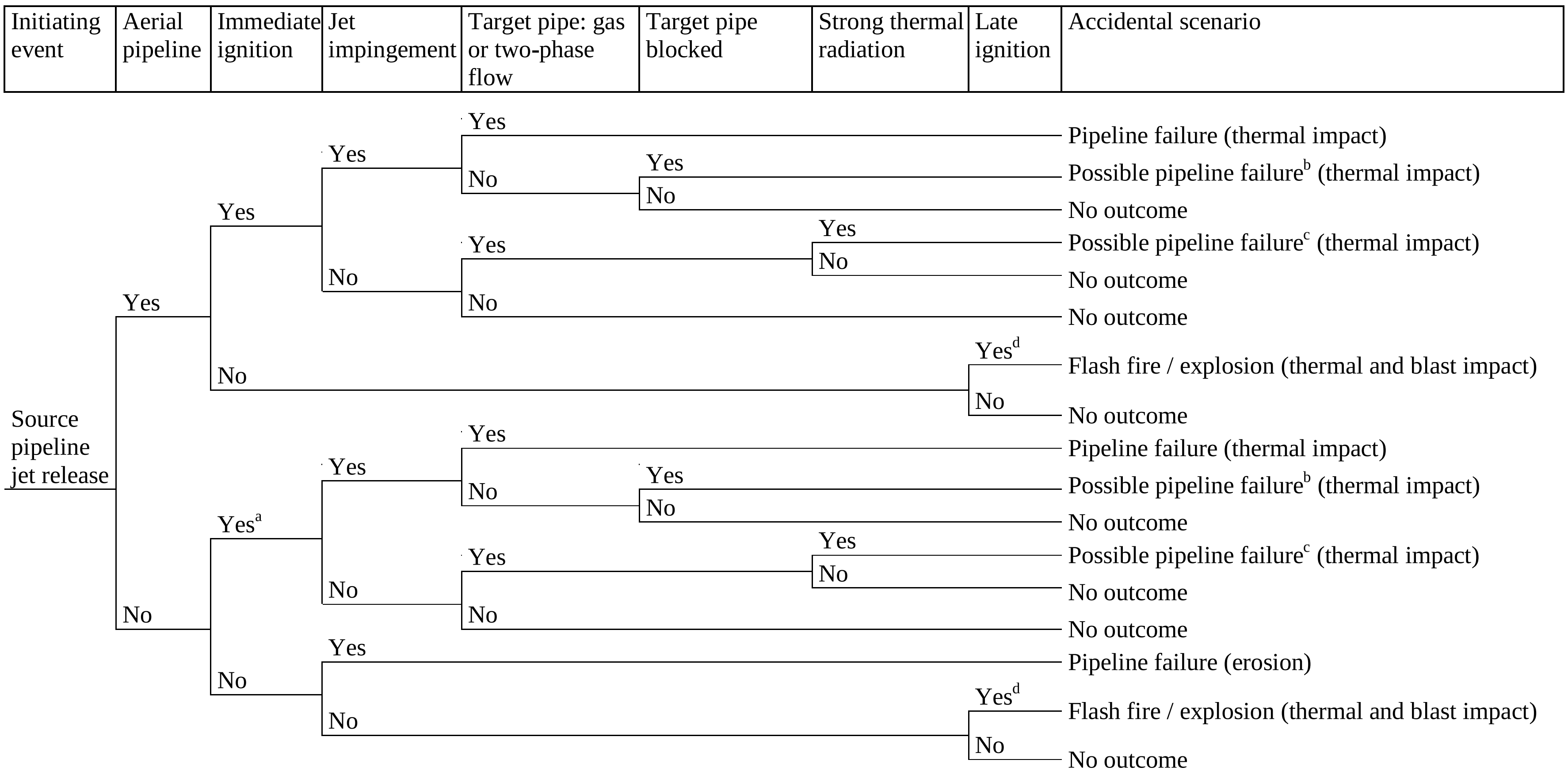
[34] CONCAWE (Conservation of Clean Air and Water in Europe) 2013, Performance of European cross-country oil pipelines. Statistical summary of reported spillages in 2012 and since 1971. https://www.concawe.eu/DocShareNoFrame/docs/1/CKMDDNNALDOOKANCINIAI

HPMVEVCW69YP3PDWK9DWDPW/CEnet/docs/DLS/Rpt_13-12-2014-01028-01-E.pdf

[35] EGIG (European Gas pipeline Incident data Group) 2011, Gas pipeline incidents, 8th Report of the European Gas pipeline Incident Data group, EGIG 11.R.0402.

FIGURE CAPTIONS

Fig. 1. Domino effect sequences following a jet release from the source pipe.
Fig. 2. Jet impingement between pipes of equal diameter.
Fig. 3. Angular sector of the source pipe that can contain holes implying risk of impingement.
Fig. 4. Overall angle covered by a jet that could affect the target pipe.
Fig. 5. Physical limits of the overall angle that can be covered by a jet.
Fig. 6. Selected geometrical variables concerning the probability model.
Fig. 7. Domino effect probability as a function of the distance between source and target pipes with the same diameter, *D*.
Fig. 8. Case of a source pipe with larger diameter than a target pipe.
Fig. 9. Domino effect probability as a function of the distance between source and target pipes, for the configurations of Table 1 (ID 3, 4, 5 and 6). Symbols with open interiors correspond to real distances for each scenario.
Fig. 10. Domino effect probability as a function of target diameter and distance between pipes for 6 in-diameter source pipe.
Fig. 11. Domino effect probability as a function of target diameter and distance between pipes for 48 in-diameter source pipe.
Fig. 12. Reach of jet fire flames.



[a] Only if the jet or a first explosion creates a crater.
[b] Jet fire heating will increase pressure and could increase pipe wall temperature.
[c] Heating of pipe wall could be excessive.
[d] Depending on meteorological conditions.

Fig. 1.

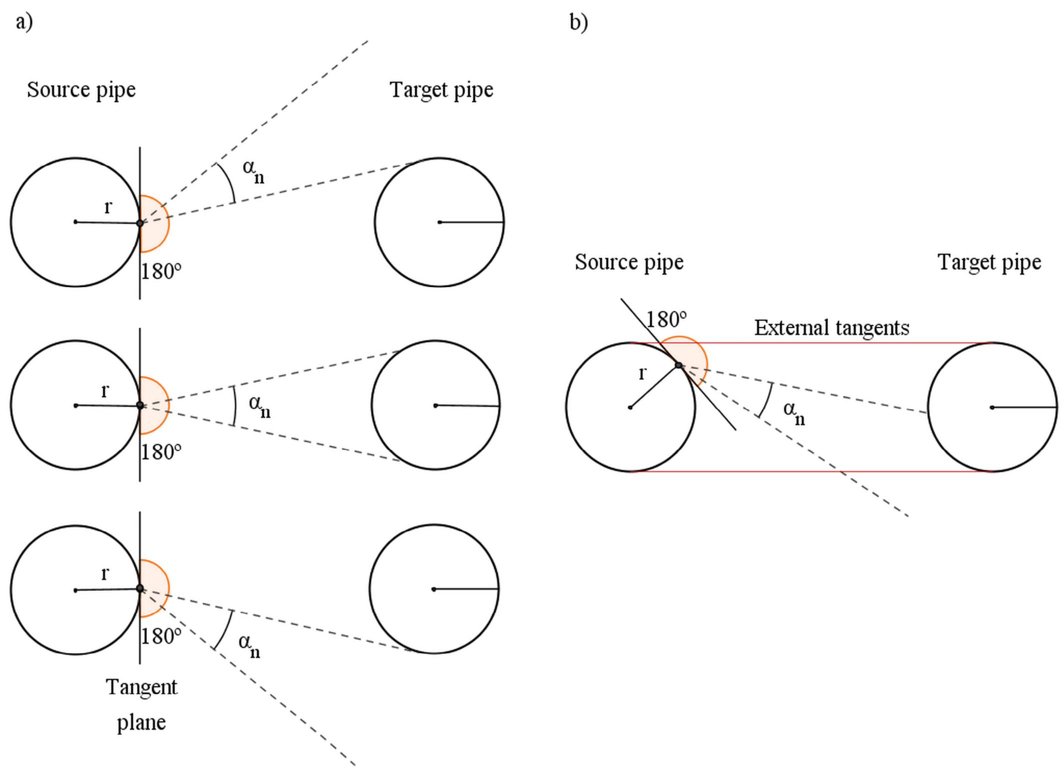

a)
b)
Source pipe
Target pipe
r
α_n
180°
Tangent
plane
Source pipe
Target pipe
External tangents
180°
r
α_n

Fig. 2.

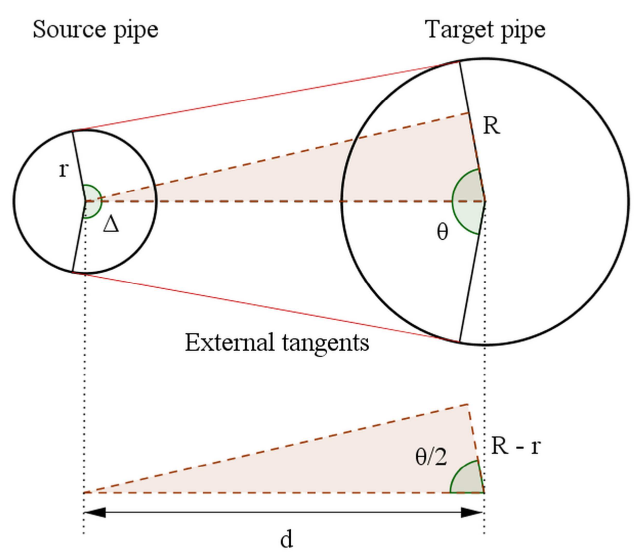

Source pipe
Target pipe
R
r
Δ
θ
External tangents
θ/2
R - r
d

Fig. 3.

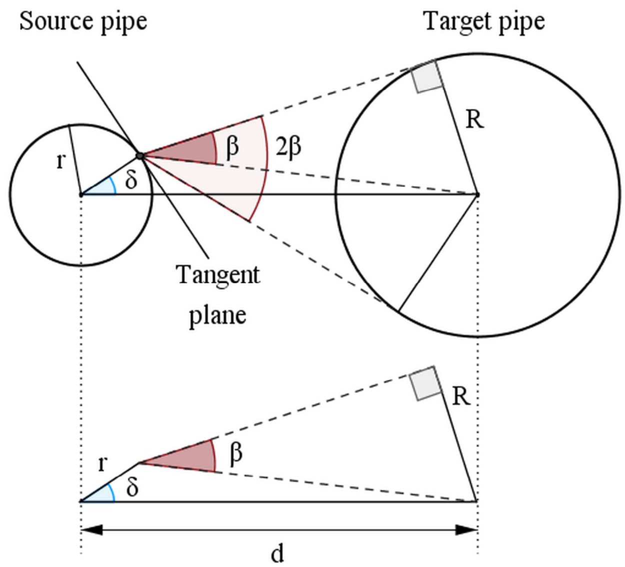

Source pipe
Target pipe
R
r
β
2β
δ
Tangent
plane
R
r
β
δ
d

Fig. 4.

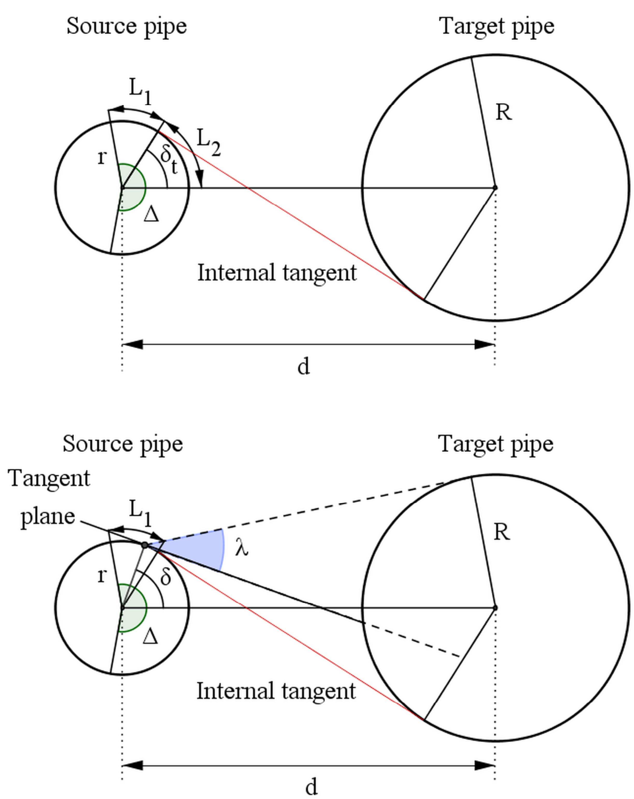

Source pipe
Target pipe
L_1
L_2
r
δ_t
Δ
R
Internal tangent
d
Source pipe
Target pipe
Tangent
plane
L_1
λ
r
δ
Δ
R
Internal tangent
d

Fig. 5.

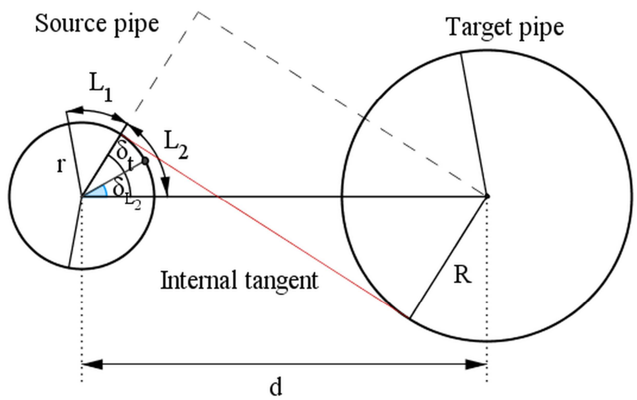

Source pipe
Target pipe
L_1
L_2
r
δ_t
δ_{L_2}
Internal tangent
R
d

Fig. 6.

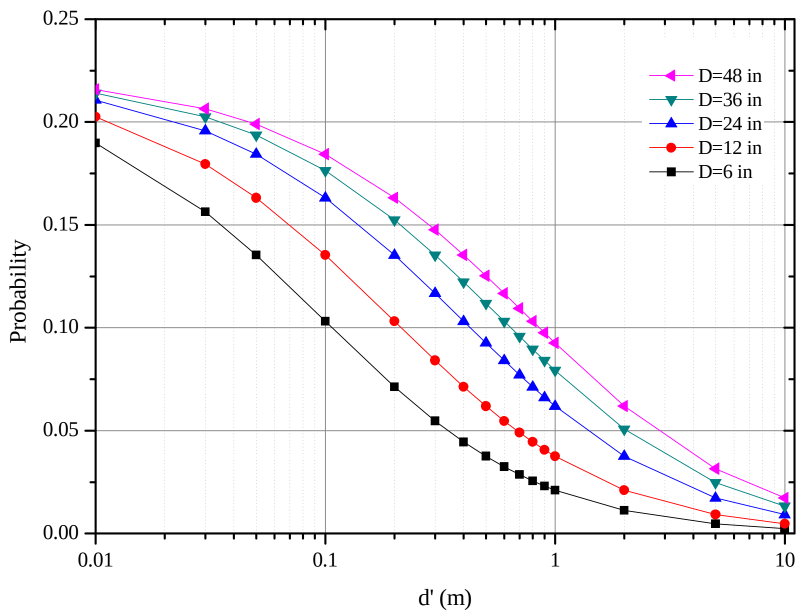
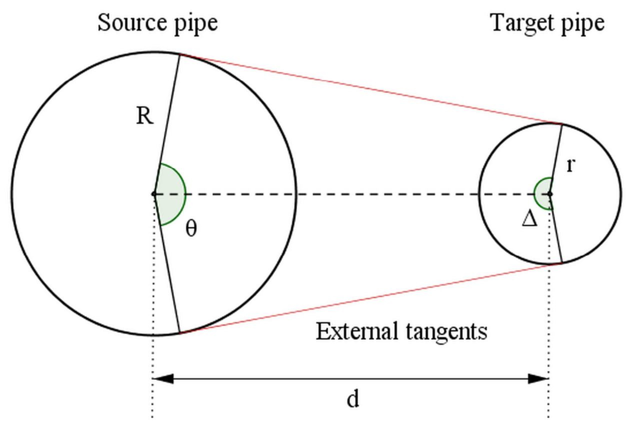
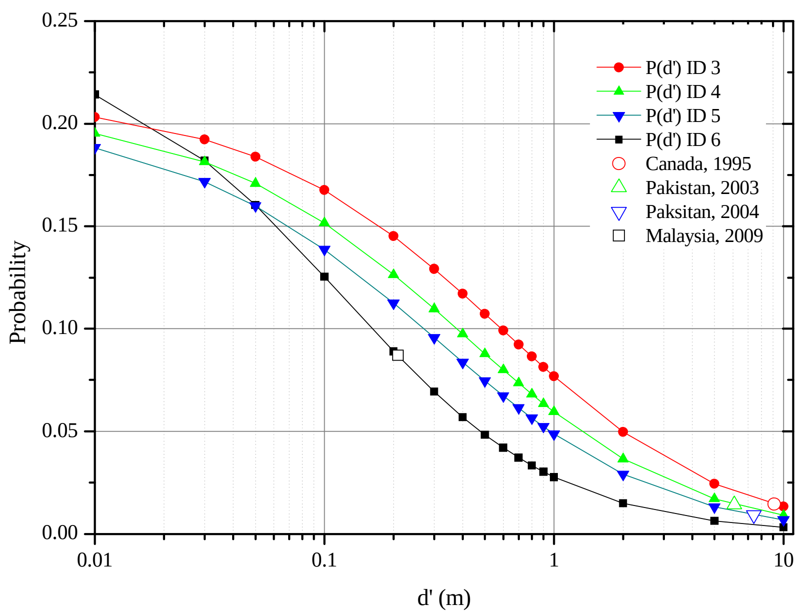

0.25
0.20
0.15
0.10
0.05
0.00
Probability
0.01
0.1
1
10
d' (m)
D=48 in
D=36 in
D=24 in
D=12 in
D=6 in

Fig. 7.



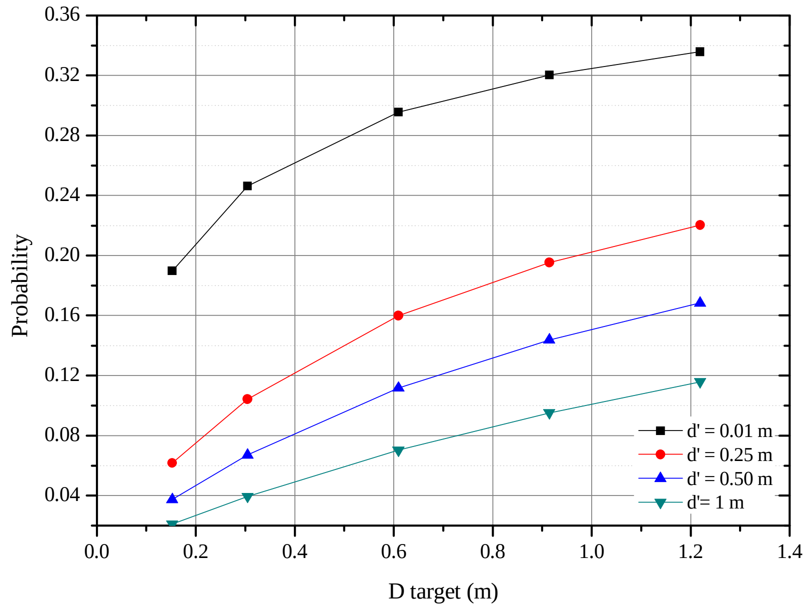
Source pipe
Target pipe
R
r
θ
Δ
External tangents
d

Fig. 8.



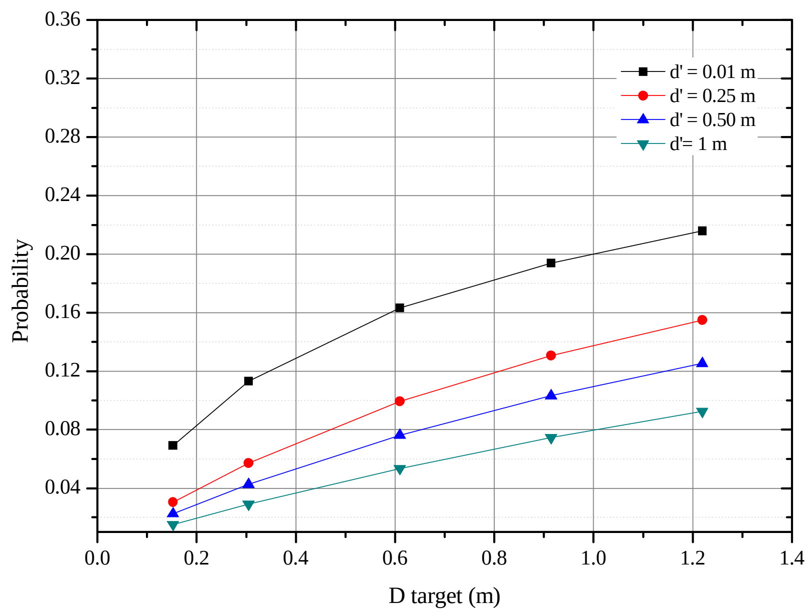
0.25
0.20
0.15
0.10
0.05
0.00
0.01
0.1
1
10
Probability
d' (m)
P(d') ID 3
P(d') ID 4
P(d') ID 5
P(d') ID 6
Canada, 1995
Pakistan, 2003
Paksitan, 2004
Malaysia, 2009

Fig. 9.



0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
Probability
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
D target (m)
d' = 0.01 m
d' = 0.25 m
d' = 0.50 m
d'= 1 m

Fig. 10.



0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
Probability
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
D target (m)
d' = 0.01 m
d' = 0.25 m
d' = 0.50 m
d'= 1 m

Fig. 11.

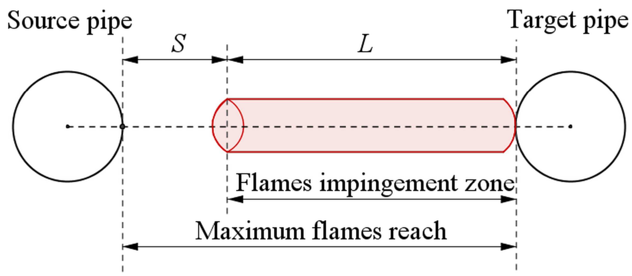

Source pipe
Target pipe
S
L
Flames impingement zone
Maximum flames reach

Fig. 12.

Figure 2

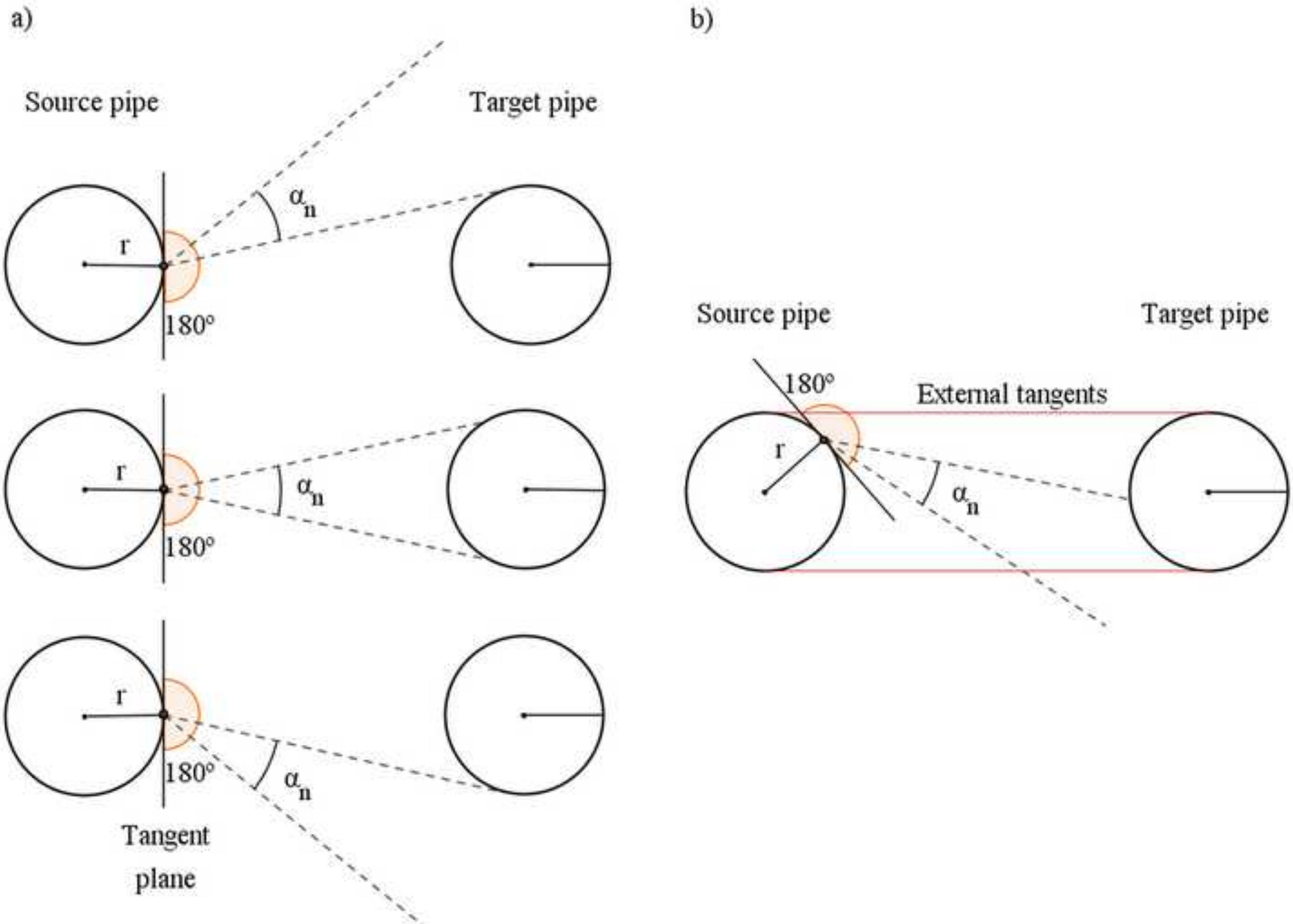

a)
Source pipe
Target pipe
r
α_n
180°
r
α_n
180°
r
α_n
180°
Tangent
plane
b)
Source pipe
Target pipe
180°
External tangents
r
α_n

Figure 3

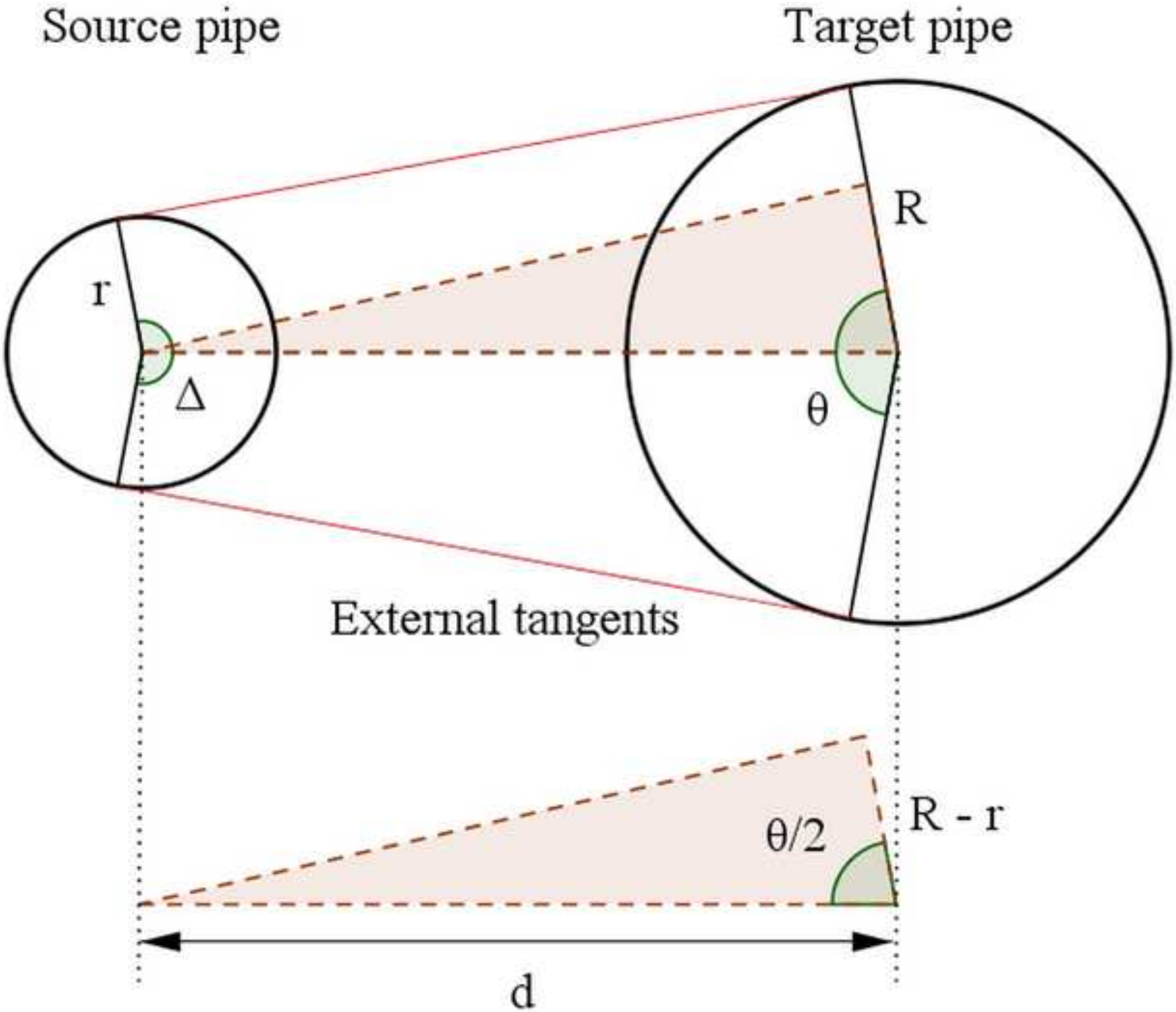


Figure 4

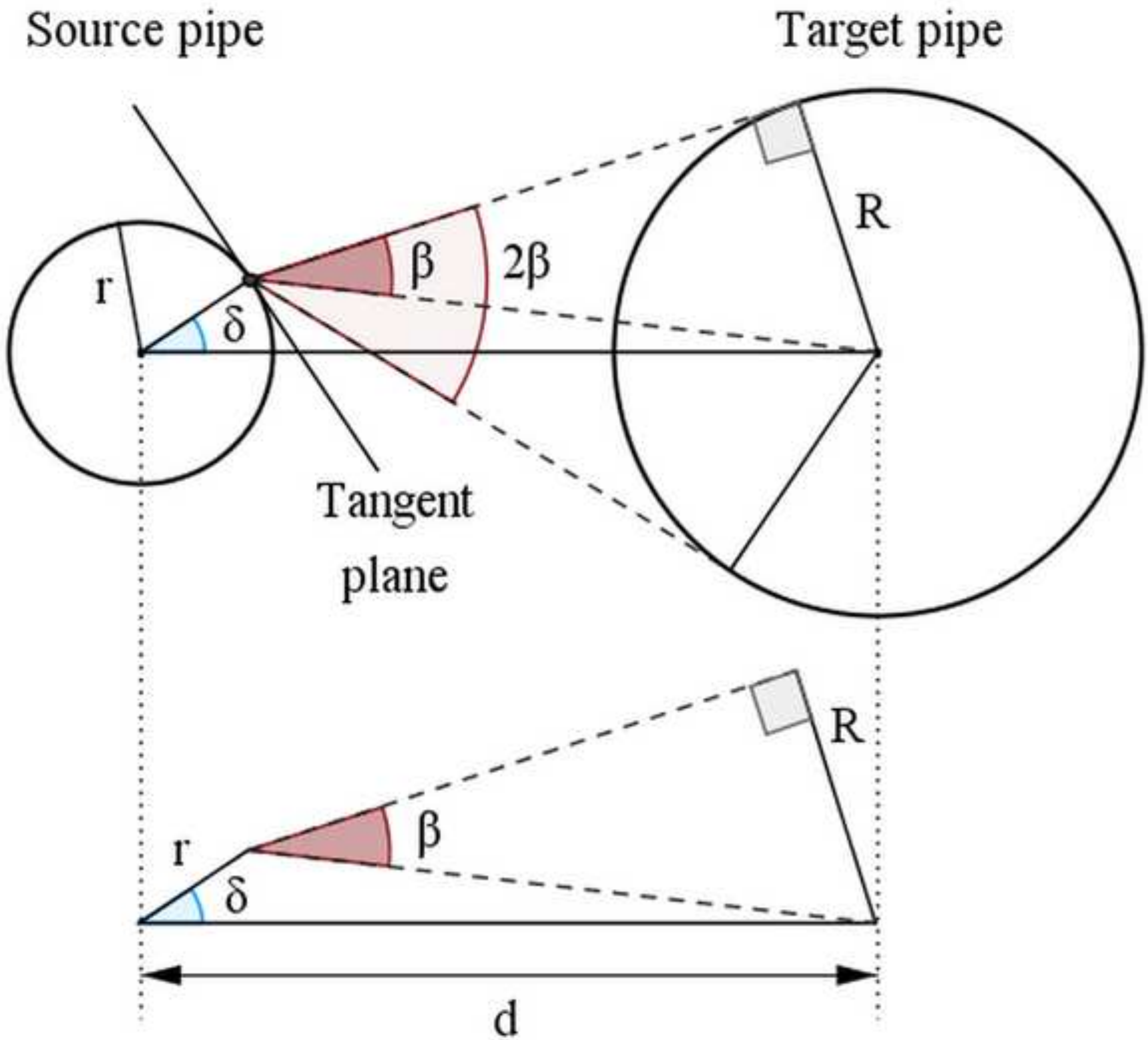
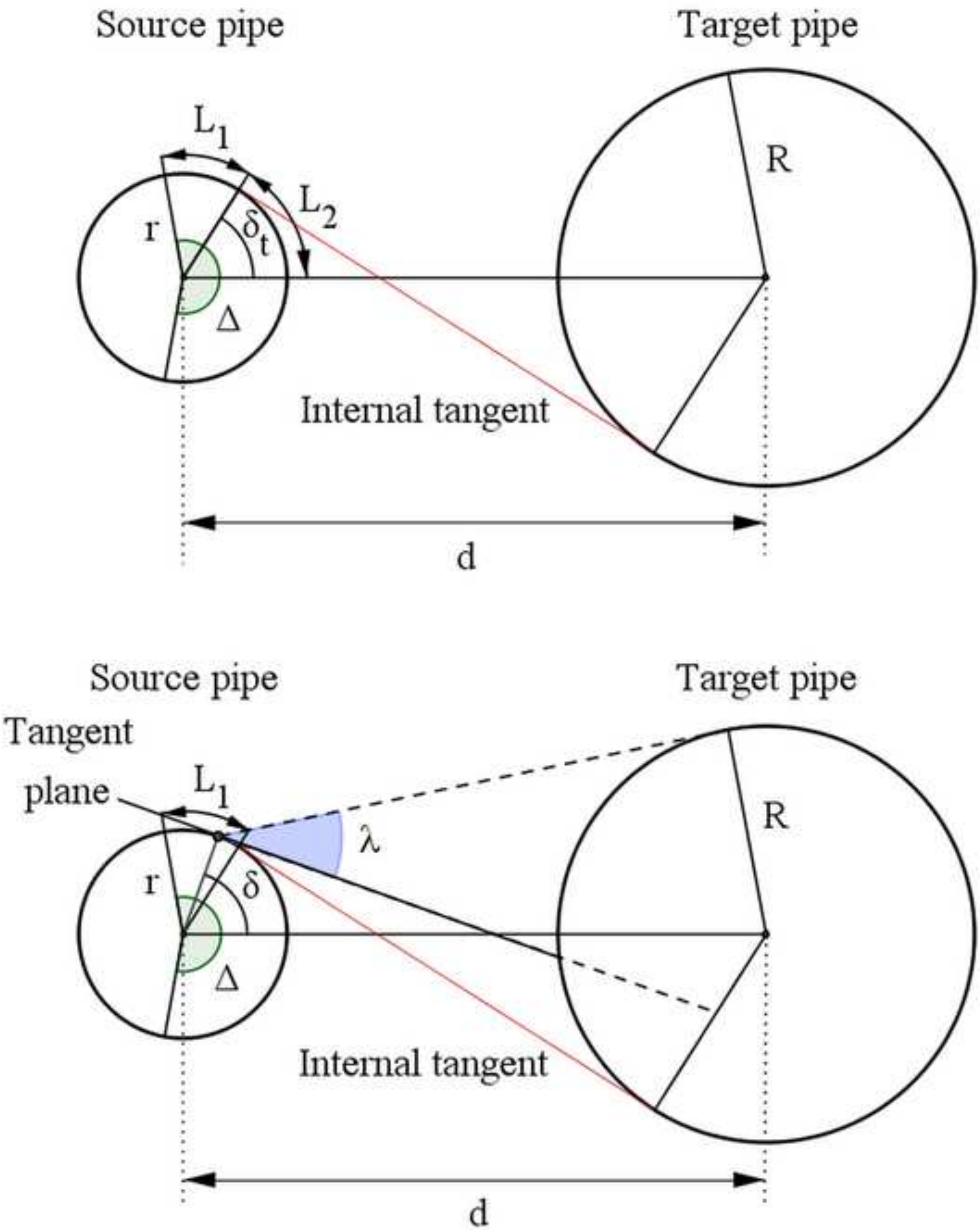
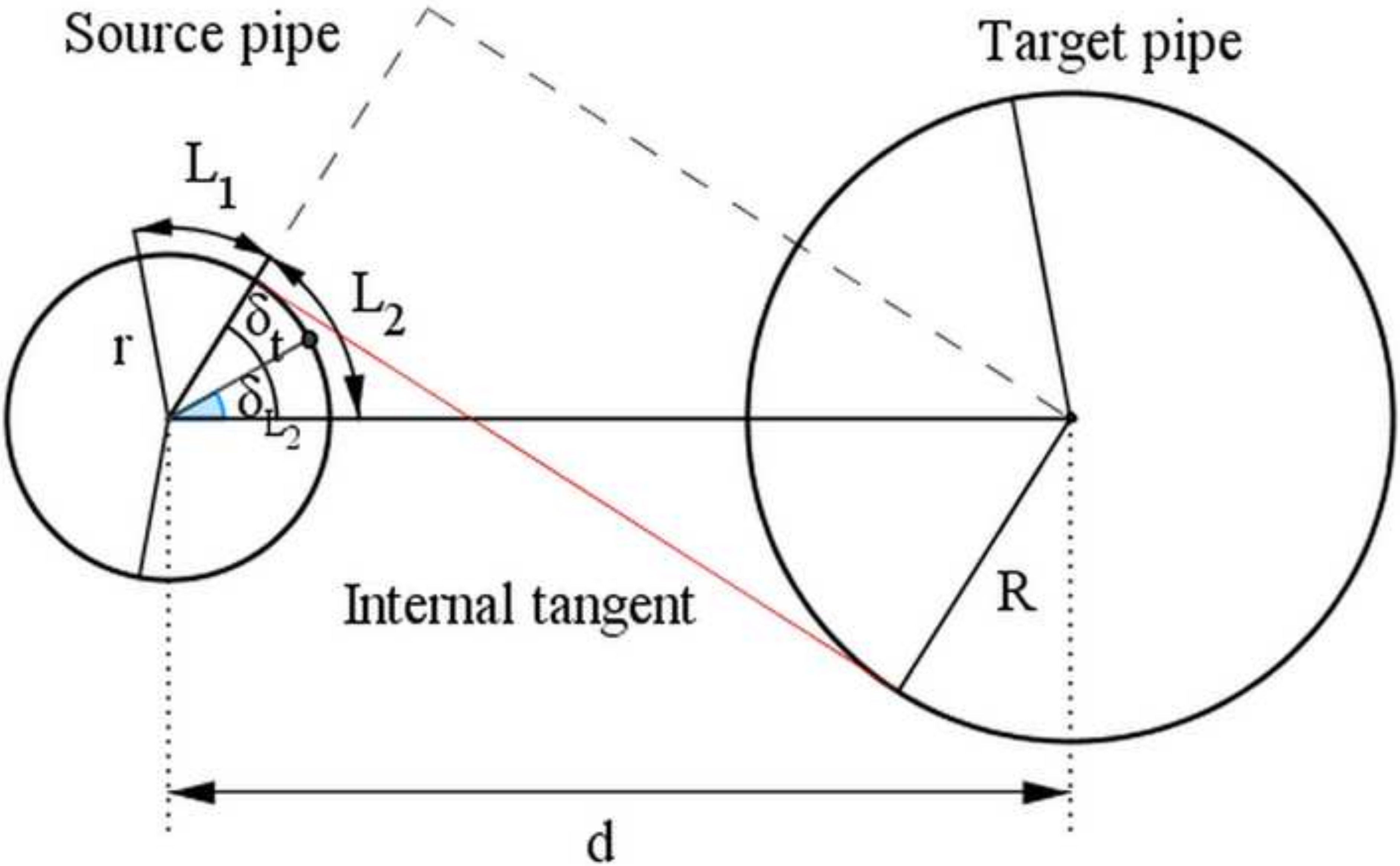


Figure 5



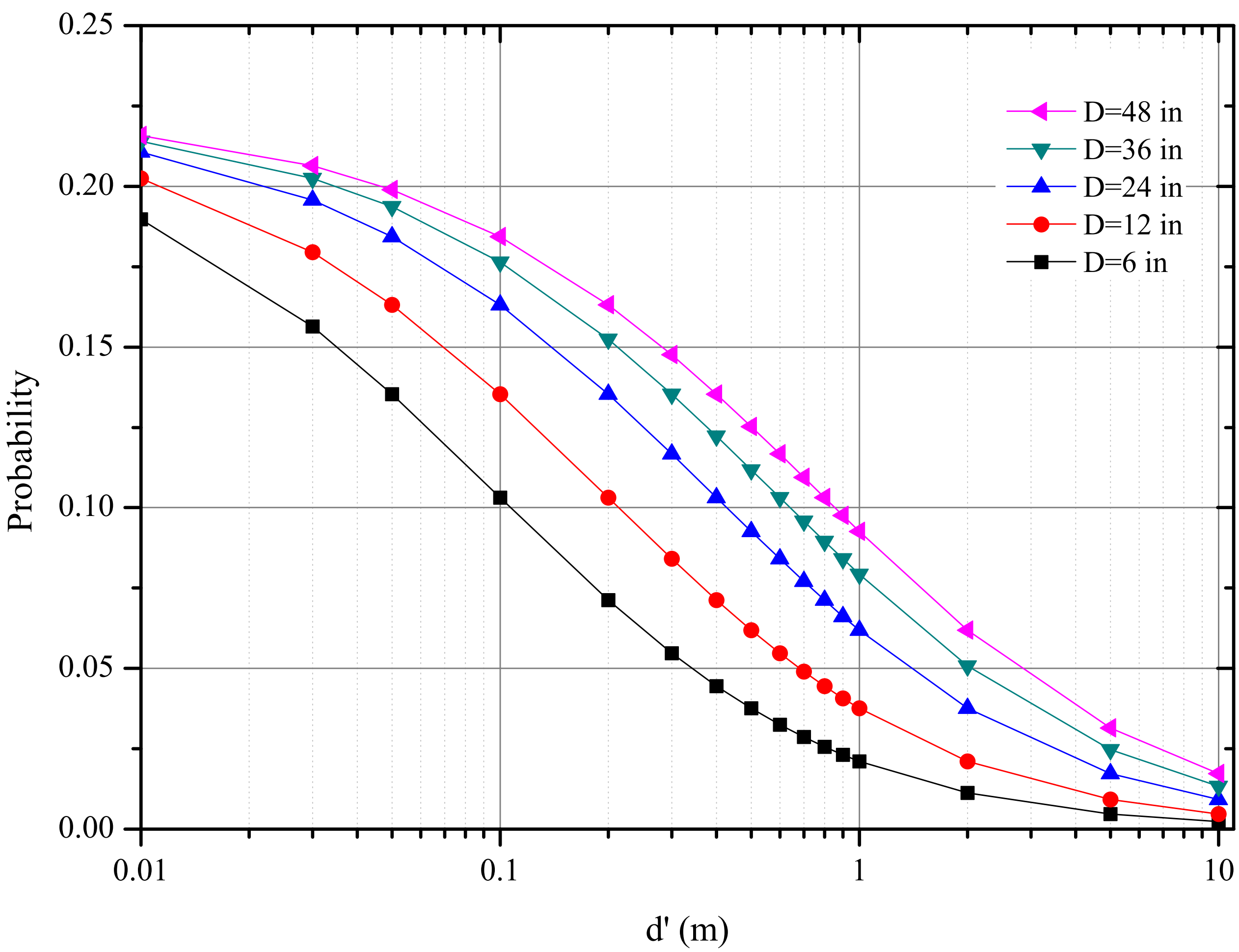
Source pipe
Target pipe
L1
L2
R
r
δt
Δ
Internal tangent
d
Source pipe
Target pipe
Tangent
plane
L1
R
λ
r
δ
Δ
Internal tangent
d

Figure 6



Source pipe
Target pipe
L_1
L_2
r
δ_t
δ_{L_2}
R
Internal tangent
d

Figure 7



0.25
0.20
0.15
0.10
0.05
0.00
0.01
0.1
1
10
Probability
d' (m)
D=48 in
D=36 in
D=24 in
D=12 in
D=6 in

Figure 8

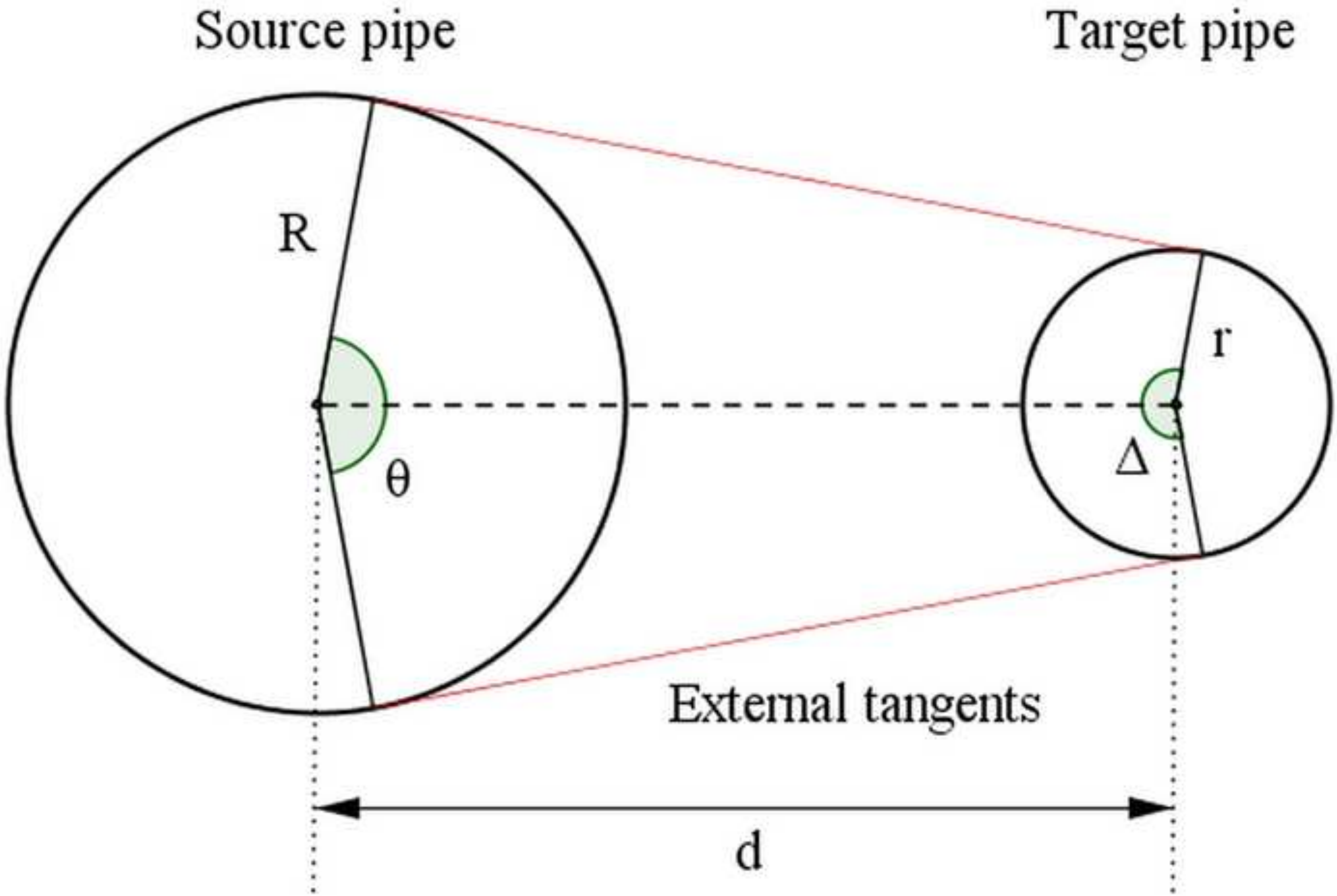
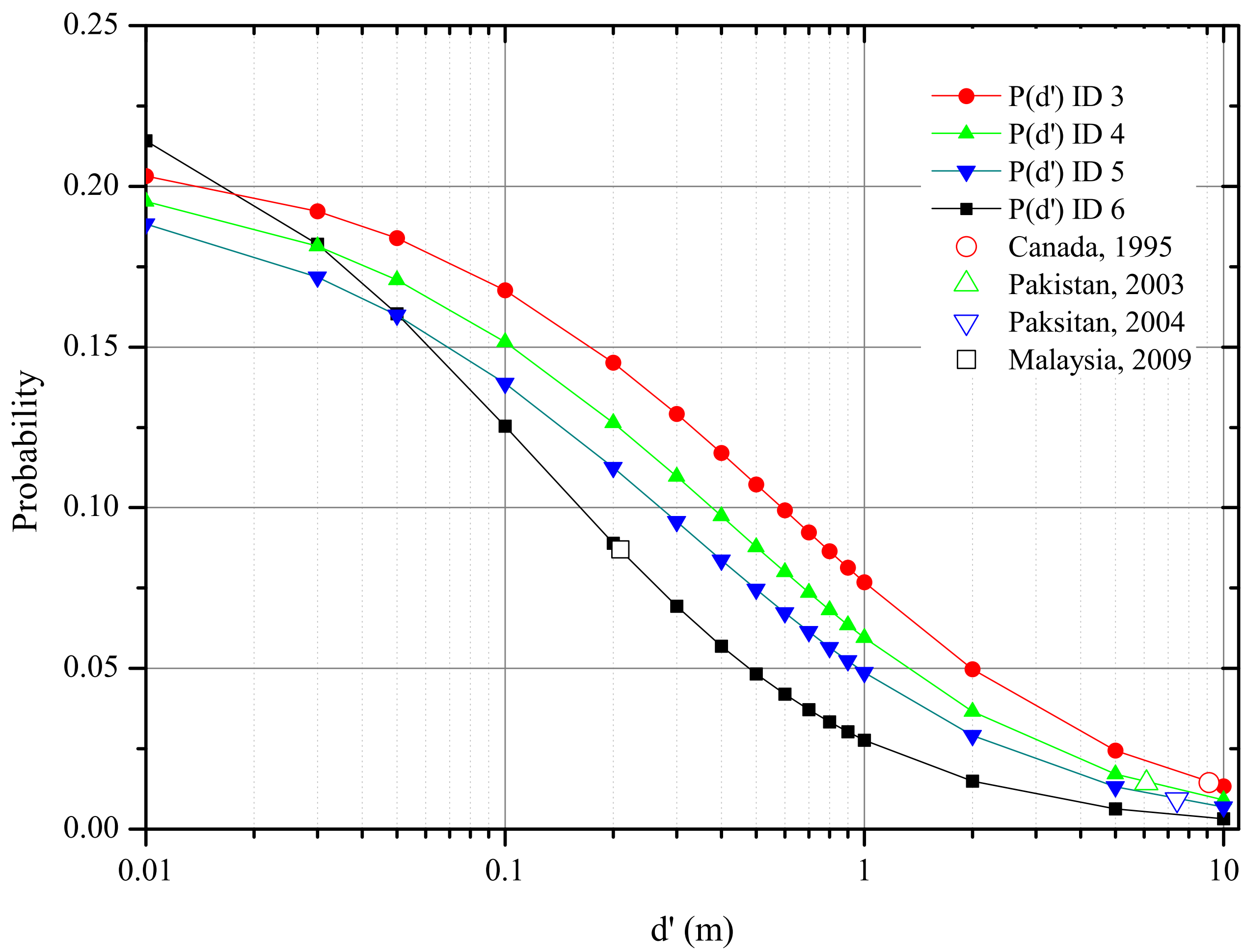


Figure 9



0.25
0.20
0.15
0.10
0.05
0.00
0.01
0.1
1
10
Probability
d' (m)
P(d') ID 3
P(d') ID 4
P(d') ID 5
P(d') ID 6
Canada, 1995
Pakistan, 2003
Paksitan, 2004
Malaysia, 2009

Figure 10

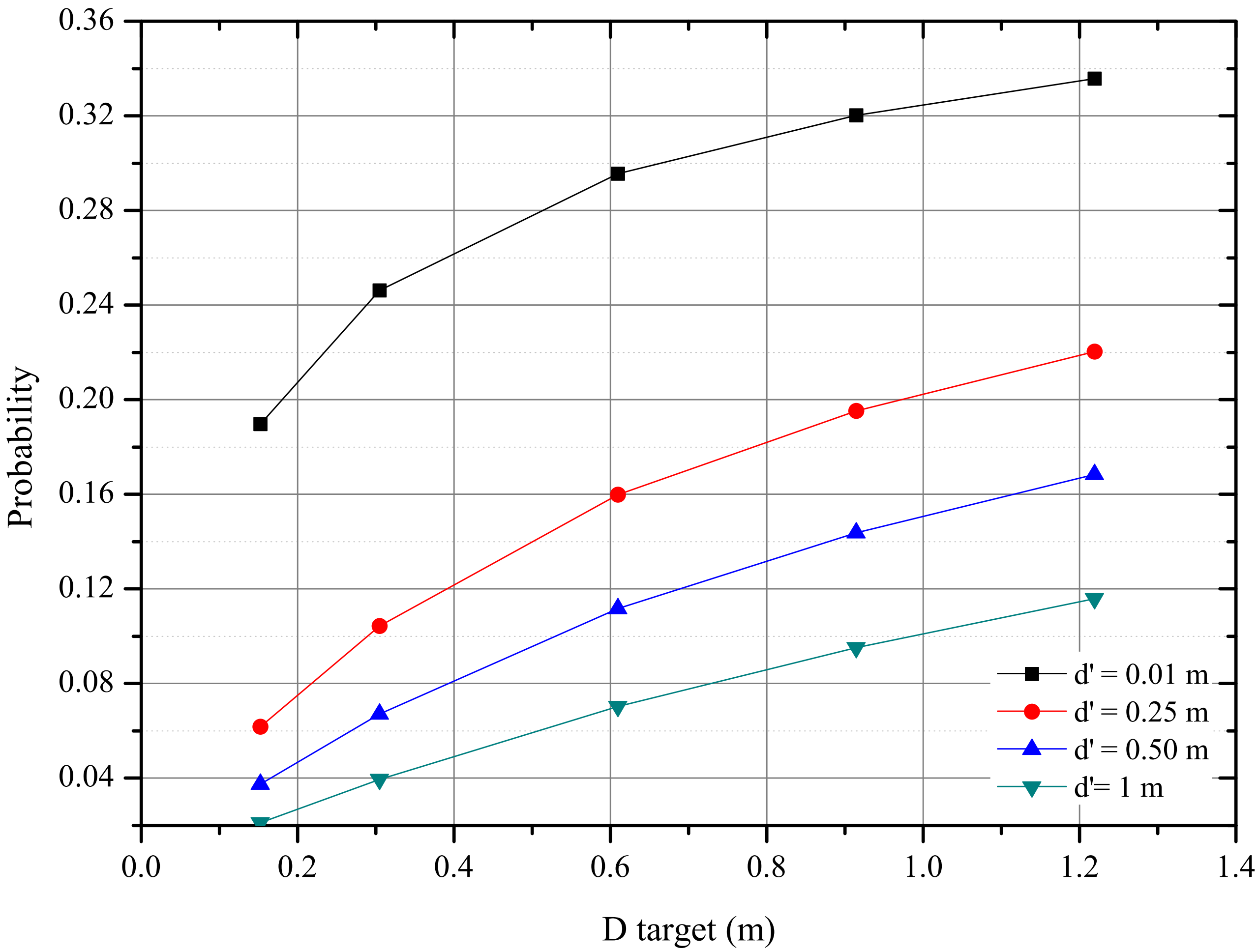
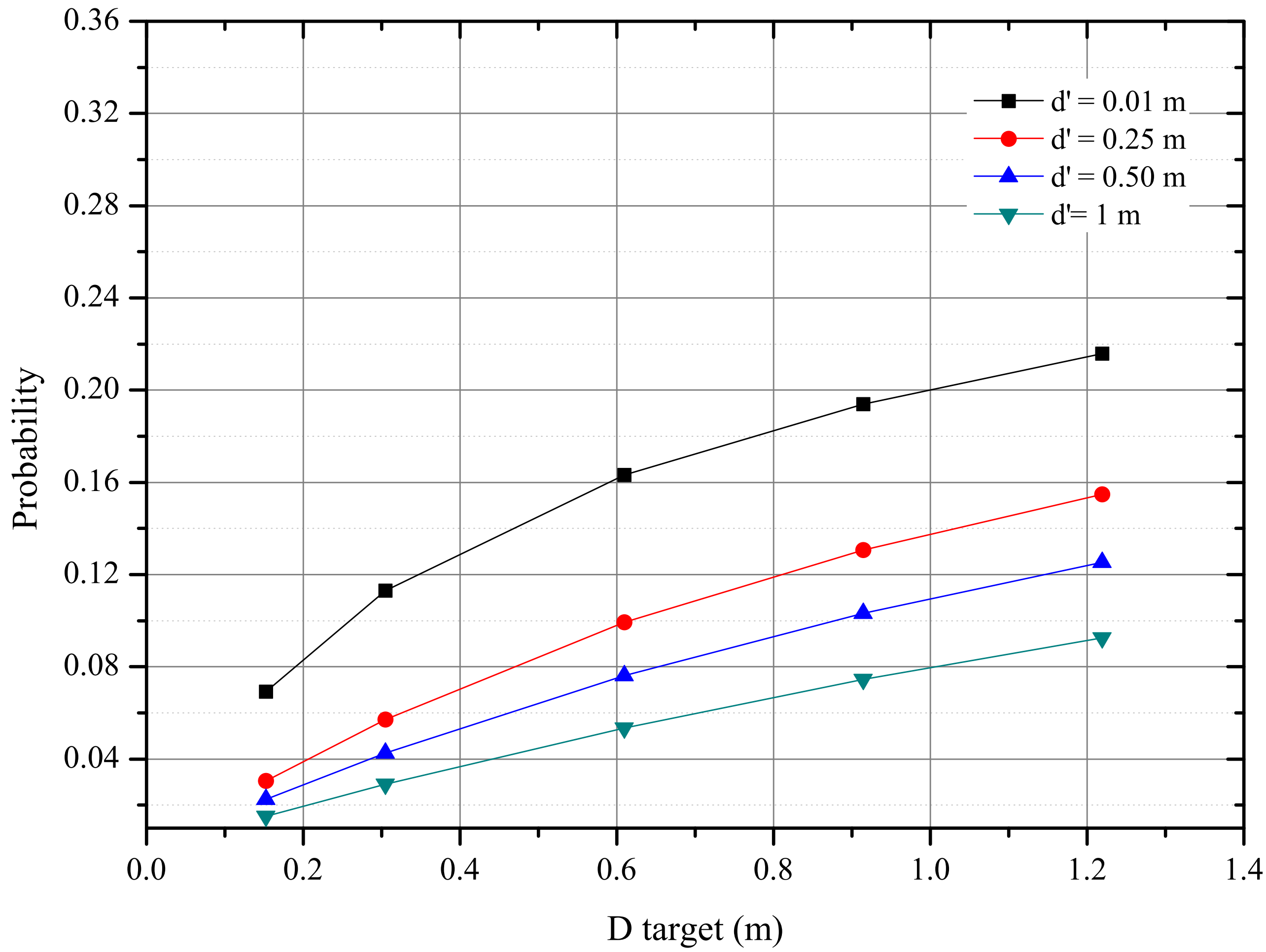
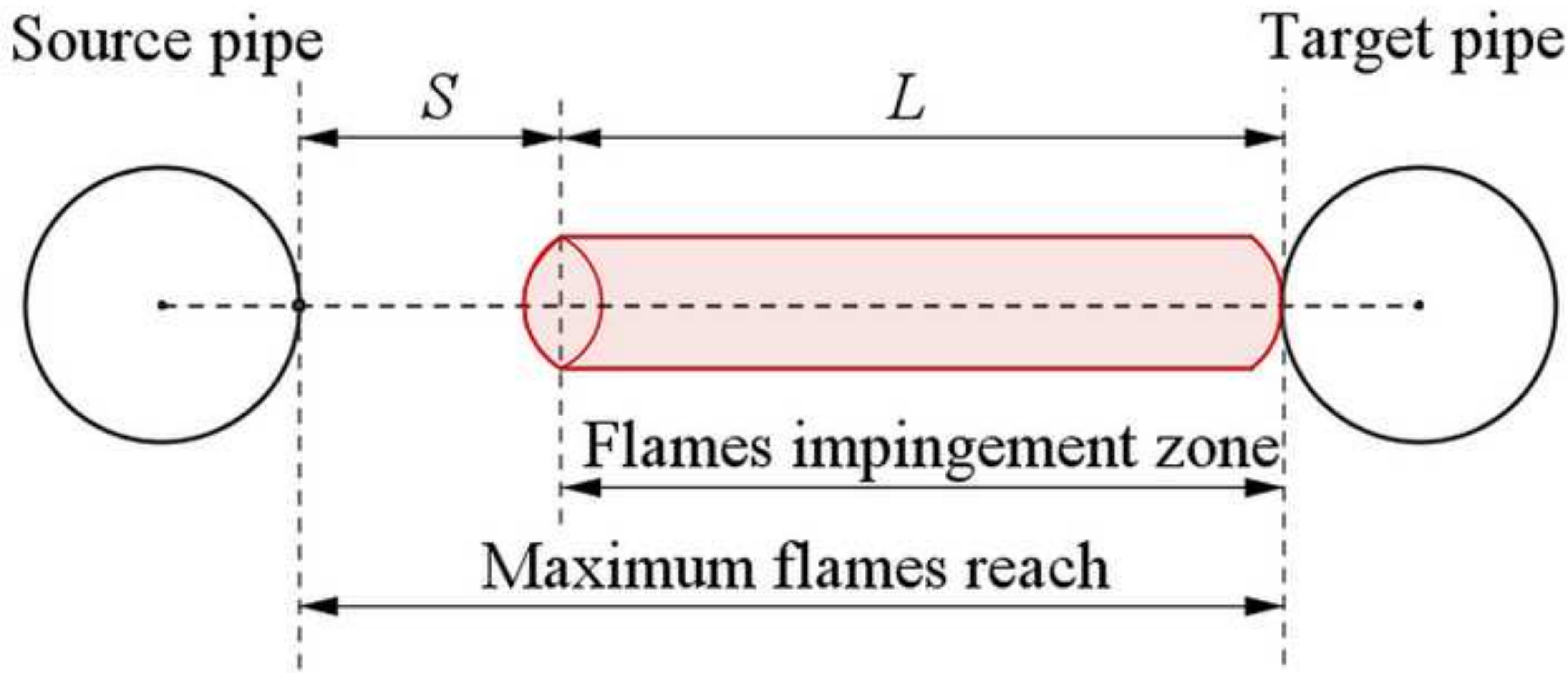

0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
Probability
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
D target (m)
d' = 0.01 m
d' = 0.25 m
d' = 0.50 m
d'= 1 m

Figure 11



0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
Probability
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
D target (m)
d' = 0.01 m
d' = 0.25 m
d' = 0.50 m
d'= 1 m

Figure 12


Source pipe
Target pipe
S
L
Flames impingement zone
Maximum flames reach